Defense Threat Reduction Agency
8725 John J. Kingman Road, MS
6201 Fort Belvoir, VA 22060-6201

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TECHNICAL REPORT

Radiological Health Protection Issues Associated with Use of Active Detection Technology Systems for Detection of Radioactive Threat Materials

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July 2013

HDTRA1-09-C-0040

Prepared by:
National Council on Radiation
Protection and Measurements
7910 Woodmont Avenue
Suite 400
Bethesda, MD 20814

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Commentary from the National Council on Radiation Protection and Measurements (NCRP) Scientific Committee 1-19. NCRP was asked to provide a review of health protection and safety issues specifically for the use of active detection technology security systems. It addresses important factors in the design and testing of ADT systems that must be given attention prior to their deployment.

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Conversion Factors for U.S. Customary to metric (SI) units of measurement.

MULTIPLY ⟶ BY ⟶ TO GET

TO GET ⟵ BY ⟵ DIVIDE

angstrom	1.000 000 x E -10	meters (m)
atmosphere (normal)	1.013 25 x E +2	kilo pascal (kPa)
bar	1.000 000 x E +2	kilo pascal (kPa)
barn	1.000 000 x E -28	meter^2 (m^2)
British thermal unit (thermochemical)	1.054 350 x E +3	joule (J)
calorie (thermochemical)	4.184 000	joule (J)
cal (thermochemical/cm^2)	4.184 000 x E -2	mega joule/m^2 (MJ/m^2)
curie	3.700 000 x E +1	*giga bacquerel (GBq)
degree (angle)	1.745 329 x E -2	radian (rad)
degree Fahrenheit	$t_k = (t^{o}f + 459.67)/1.8$	degree kelvin (K)
electron volt	1.602 19 x E -19	joule (J)
erg	1.000 000 x E -7	joule (J)
erg/second	1.000 000 x E -7	watt (W)
foot	3.048 000 x E -1	meter (m)
foot-pound-force	1.355 818	joule (J)
gallon (U.S. liquid)	3.785 412 x E -3	meter^3 (m^3)
inch	2.540 000 x E -2	meter (m)
jerk	1.000 000 x E +9	joule (J)
joule/kilogram (J/kg) radiation dose absorbed	1.000 000	Gray (Gy)
kilotons	4.183	terajoules
kip (1000 lbf)	4.448 222 x E +3	newton (N)
kip/inch^2 (ksi)	6.894 757 x E +3	kilo pascal (kPa)
ktap	1.000 000 x E +2	newton-second/m^2 (N-s/m^2)
micron	1.000 000 x E -6	meter (m)
mil	2.540 000 x E -5	meter (m)
mile (international)	1.609 344 x E +3	meter (m)
ounce	2.834 952 x E -2	kilogram (kg)
pound-force (lbs avoirdupois)	4.448 222	newton (N)
pound-force inch	1.129 848 x E -1	newton-meter (N-m)
pound-force/inch	1.751 268 x E +2	newton/meter (N/m)
pound-force/foot^2	4.788 026 x E -2	kilo pascal (kPa)
pound-force/inch^2 (psi)	6.894 757	kilo pascal (kPa)
pound-mass (lbm avoirdupois)	4.535 924 x E -1	kilogram (kg)
pound-mass-foot^2 (moment of inertia)	4.214 011 x E -2	kilogram-meter^2 (kg-m^2)
pound-mass/foot^3	1.601 846 x E +1	kilogram-meter^3 (kg/m^3)
rad (radiation dose absorbed)	1.000 000 x E -2	**Gray (Gy)
roentgen	2.579 760 x E -4	coulomb/kilogram (C/kg)
shake	1.000 000 x E -8	second (s)
slug	1.459 390 x E +1	kilogram (kg)
torr (mm Hg, 0^0 C)	1.333 22 x E -1	kilo pascal (kPa)

*The bacquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.

**The Gray (GY) is the SI unit of absorbed radiation.

Preface

The National Council on Radiation Protection and Measurements (NCRP) is preparing a series of publications related to the use of active detection technology (ADT) security screening systems for the detection at standoff distances of special nuclear material (SNM) and other radioactive materials that could represent a terrorist threat to public health. The ADT systems currently under consideration by the Defense Threat Reduction Agency (DTRA) will utilize beams of photons such as high-intensity bremsstrahlung radiation, and particle beams of protons, neutrons, or muons to elicit radiation signatures that can provide a long-range capability for detecting in cargo containers the presence of SNM of concern for acts of terrorism.

The initial NCRP publication on this subject is Commentary No. 21 (2011), which evaluates the health protection aspects of designing and deploying ionizing radiation screening systems in a manner consistent with meeting the objectives of the fundamental principles of radiation protection [namely, justification, optimization (ALARA), and limitation of exposure]. The primary emphasis of Commentary No. 21 is on applying these principles in the design and deployment of any security screening system that utilizes ionizing radiation, including ADT security systems.

This Commentary evaluates health protection and safety issues specifically for the use of ADT security systems. It addresses important factors in the design and testing of ADT systems that must be given attention prior to their deployment in maritime or land-based operational settings. This Commentary also addresses the following issues related to the possible future use of ADT security screening systems:

- potential exposures to radiation from ADT systems to the health of operating personnel, bystanders, and others in the inspected areas;

- design and operational factors that must be considered in assessing the safe and efficient operation of ADT systems;
- radiation protection design considerations, engineering controls (*e.g.*, shielding, barriers, system performance indicators, and safety interlocks), and operational practices and procedures (*e.g.*, operator training, recording of ADT operating parameters, and quality control test results) that must be considered in ADT system design and deployment.

This Commentary was prepared by NCRP Scientific Committee 1-19. Serving on the Committee were:

John F. Ahearne, *Chairman*
Sigma Xi, The Scientific Research Society
Research Triangle Park, North Carolina

Members

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Memorial Sloan-Kettering Cancer Center
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Thomas S. Tenforde
President

Contents

1. Introduction

The Defense Threat Reduction Agency (DTRA) is sponsoring research into a range of technologies intended to aid in the early detection and interdiction of special nuclear material (SNM) and other radioactive materials that could represent a significant threat to homeland security. The DTRA program has the goal of developing long-range, standoff active detection technology (ADT) systems that use radiation to stimulate detectable signatures from radioactive threat materials at ranges of 100 to 1,000 m. These systems include high-intensity bremsstrahlung radiation, monoenergetic gamma-ray sources, and particulate radiations including neutrons, protons and muons. The resulting signatures include prompt and delayed neutron and gamma emissions from induced fission events, x rays from muon interactions with high atomic number (*Z*) materials, and other signatures resulting from particulate or electromagnetic radiation interactions with SNM and other potential radiological weapons materials. The stimulated signatures would facilitate long-range detection of the threat materials using detectors that are spatially and temporally linked to the ADT radiation sources.

These ADT radiation sources could pose a health risk to operating personnel, bystanders, and individuals in the inspected areas. As used in Commentary No. 21 (NCRP, 2011), the term "bystanders" refers to workers involved with the shipping or handling of suspicious containers or members of the public who are in the area but ignorant of any SNM and unaware that they might be at risk of radiation exposure. Those who are clearly identified as knowingly transporting SNM are "terrorists" as referred to in Chapter 113B: 2332b and 2339 of Title 18, U.S. Code and not addressed in this Commentary.

With a reasonable set of assumptions, estimated doses[1] from use of ADT systems can approach a dose limit of 5 mSv. Designing and operating an ADT system that can meet that limit without any margin of safety will be quite challenging. These radiation doses involve direct radiation exposures of individuals and secondary exposures associated with the production of activated materials. Assessing potential radiation doses from ADT systems will assist DTRA in making decisions and developing policies on the types and deployment of candidate ADT systems with the objective of optimizing both the effectiveness of these technologies and the protection of human health based on fundamental radiation protection principles and practices. The analysis presented in this Commentary is predicated upon infrequent and not repeated exposures. As described later in this Commentary, repeated exposures can present potential doses exceeding the dose limit.

U.S. citizens have become accustomed to screening at airports, entering federal buildings, and at some other venues, such as major sports events. A major difference between that screening and the detection addressed by Commentary No. 21 (NCRP, 2011) and this Commentary is that the personal screening is announced in advance, it is performed voluntarily (the individual can decide not to enter), and the screening equipment is in plain view of the persons being screened. In the present case, the vessels and items being screened and the individuals associated with them are not volunteers, they may not be aware of the process, and the screening equipment may be hidden.

While concerns about radiation exposures are important, there may be times when issues of health effects and privacy need to be carefully balanced with national security concerns. This

[1] The term "dose" as used in this Commentary refers to effective dose from ionizing radiation. Dose terminology and associated dose limits are described in Section 4.3.

facet increases the importance of obtaining enough sufficiently accurate information to justify the ADT screening.

DTRA commissioned two commentaries from NCRP. Commentary No. 21 addresses broad radiation protection issues raised by the use of ADT systems while this Commentary goes into greater technological detail to define the factors to be considered in the design and deployment of the ADT systems.

This Commentary:

- examines the potential radiation doses from ADT systems to operating personnel, bystanders, and other individuals in the inspected areas; and design and operational factors that must be considered in assessing the safety and efficiency of ADT systems.
- provides recommendations on the research, development, and fielding of ADT systems under consideration by DTRA to optimize the effective and safe use of these systems, address the full range of safety and health concerns associated with the deployment of ionizing radiation systems that currently exist, are under development, or may be developed in the future for the detection and interdiction of weapons of mass destruction (WMD) special nuclear material (SNM) devices that could be used in acts of terrorism.
- endorses the recommendations and analyses of Commentary No. 21 (NCRP, 2011) of the issues of importance in the development and deployment of security systems involving ionizing radiation.
- provides recommendations related to radiation protection design considerations, engineering controls, and operational practices and procedures for the various ADTs

that are being evaluated by DTRA and its contractors. The technologies under consideration for ADT systems will employ radiation sources for detection of SNM and other radiological materials of possible use in WMD. It is planned for these active detection systems to be deployable at standoff ranges or in shielded configurations. Commentaries No. 21 and No. 22 will form the framework for the development of subsequent NCRP reports on specific leading candidate ADT systems under consideration by DTRA.

This Commentary is meant to apply to the use of ADT in the United States and at foreign sites. Use in non-U.S. locations will require negotiation by an appropriate U.S. agency with foreign governments.

This Commentary addresses the several types of ADT systems being considered by DTRA at the time of writing this Commentary. However, only Photonuclear Inspection and Threat Assessment System (PITAS) has progressed to the demonstration phase. Therefore, many of the tasks assigned to NCRP by DTRA must await further development of ADT systems. For this reason this Commentary presents generic recommendations.

Although only PITAS is emphasized, this Commentary is recommended for use by DTRA in developing ADT systems and operational policies, by operating personnel,and by the U.S. Congress. It also provides information to members of the public who may be interested in potential radiation exposures from ADT systems.

2. Active Detection Technology System Description

The radiation sources and detectors that can be used for determining the presence and amounts of SNM in a vessel, building, or other structure are the fundamental components of ADT systems. The use of radiation sources as an integral part of ADT systems introduces health protection issues that are not present with passive detection systems. To identify the radiological health protection issues it is necessary to understand the basic design and operation of the components of ADT systems. This section presents a description of the basic components of ADT systems and their operation. The features and operation of such systems that potentially impact human health are discussed in Section 5.

2.1 ADT Systems

The fundamental goal of SNM interdiction systems employing radiation detectors is to assess the presence or absence of a predetermined minimum amount of SNM at a specific location with a known level of confidence. An additional goal may be detection of materials that can be used to shield SNM. Passive detection systems rely on the natural (unstimulated) emission of characteristic radiations from SNM. However, the natural emissions from a source of SNM may have insufficient intensity to be detected at the desired level (mass) of SNM or SNM may be deliberately or inadvertently shielded to prevent detection by passive detection systems. In such cases certain radiation sources can be used to irradiate SNM to enhance the emission of characteristic radiations from SNM, and the emitted radiations are subsequently detected. Systems that employ radiation sources to stimulate emissions of radiation from SNM are referred to as ADT systems.

The components of an ADT system include: radiation source (typically a high-energy particle accelerator), intensity and direction control systems for the source, and detectors to detect the radiation types and energies that will characterize SNM or associated shielding. Additionally, there are components that provide utilities and protection of the ADT system. The locations, numbers, and relative orientation of ADT system components will vary according to the system design and the associated deployment requirements.

ADT systems use radiation to stimulate detectable signatures from fissile threat materials. The possible radiation types include high-intensity bremsstrahlung radiation and particulate radiations including neutrons, protons and muons. The types of interrogating radiation are discussed in more specific detail in Section 2.3. The resulting signatures include prompt and delayed neutron and gamma emissions from induced fission events, x rays from muon interactions with high-*Z* materials, and other signatures resulting from particulate or electromagnetic radiation interactions with SNM and other potential radiological weapons materials. The stimulated signatures would facilitate long-range detection of the threat materials using detectors that are spatially and temporally linked to the ADT system sources.

ADT systems may employ multiple sources of radiation and each source introduces its own set of human health protection issues. If multiple sources are used to interrogate the same suspected location of SNM, the potential severity and likelihood of potential health protection issues may increase. Use of multiple sources may also add to the complexity of analysis and evaluation of health effects.

The SNM to be located may be outdoors or inside a transport vessel, building, or other structure. The location and geometrical configuration of SNM is not expected to be known. The types, amounts and configuration of materials functioning as shielding of SNM are also expected to be unknown. These properties of SNM and its shielding are the primary sources of uncertainties of detection and characterization of SNM.

Interferences caused by induced emissions of radiations (from SNM or other materials) other than the desired type and energy of radiation may be nuisance interference for ADT system operators. However, such radiations can lead to additional health protection issues. Increases in the source intensity to improve the signal-to-noise ratio of an ADT system may lead to higher radiation doses from the system and additional health protection issues.

This Commentary analyzes several of the most plausible ADT systems, focusing on particle accelerators as the primary radiation sources. Radiation fields produced by photons, protons, muons and neutrons are considered to be the most plausible types of radiation for ADTs. Proton accelerators and electron accelerators are likely the best sources of radiation with sufficient energy and fluence rates to accomplish the goals of ADT systems. The short ionization ranges of other ions at a specific energy limit their effectiveness for use in ADT systems.

2.2 Special Nuclear Material Characterization

As noted previously, SNM is the material to be detected and characterized. The primary types of SNM being sought with ADT systems are highly-enriched uranium (HEU) and ^{239}Pu, which are radioactive materials that could be used in a nuclear explosive device. ADT systems are designed to detect the presence of a predetermined amount of SNM in a specific geometrical configuration with assumed types and amounts of shielding. The minimum amount (mass) of SNM that is to be detected by an ADT system is the parameter that has the greatest impact on system design and the associated potential for health protection issues.

Because there are numerous combinations of source amounts, geometries, and shielding, ADT systems will likely be designed and operated to minimize false rejections. One of the consequences of this strategy is higher radiation dose rates at the SNM location (and in other locations) and an associated increase in the number and potential severity of health protection issues.

2.3 Radiation Source Characteristics

Radiation sources that can be used with ADT systems are categorized according to the type of radiation emitted by the source. A basic requirement of the radiation source for an ADT system is that the radiation can cause SNM to emit a characteristic radiation subsequent to the interaction of that radiation with SNM. Another requirement of the interrogating source is that the radiation can be directed toward suspected SNM (*i.e.*, the radiation source is a directional beam). In the event that an ADT system includes an isotropic source of neutrons that is placed on a transport vessel or in a building, the source configuration would increase the area of potential exposures significantly from that of a collimated beam of radiation and would introduce additional health protection issues. The discussion of radiation sources considered for ADT systems in this section is limited to radiation beams generated by charged particle (electron and proton) accelerators.

Each radiation source considered for ADT systems can produce the desired effect in SNM through fundamental physical interactions and energy deposition in SNM. The same properties of these sources gives each source the potential to deliver a very high radiation dose to persons who might be irradiated during use of the ADT systems. The radiation doses to persons from each source depend on the radiation type, energy and fluence rate (radiation intensity) at the person's location. Factors affecting radiation doses from ADT systems are described in Section 5.

Each of the radiation sources considered for use with ADT systems has advantages and disadvantages (limitations) regarding the overall sensitivity and efficacy of the ADT system in which they are used. Likewise, the potential radiation doses to system operators and other persons in the vicinity of the operating ADT system vary considerably with type of radiation source. Assessment of potential radiation doses to personnel and bystanders is an essential part of selection of the radiation source for ADT systems and is discussed in Section 5.

There are a number of good general references on the physics and operational characteristics of particle accelerators (*e.g.*, Bryant and Johnsen, 1993; Cossairt, 2008; Edwards and Syphers, 1993; Lee, 2004; Livingood, 1961; Wangler, 1998; Wilson, 2001). A discussion of the types of radiation beams produced with these accelerators is given in the following text.

2.3.1 *Photons*

Photons in ADT applications are generated most productively through the physical process of bremsstrahlung production from high-energy electrons originating from an electron accelerator. Photon (bremsstrahlung) beams generated with electron accelerators originate from the fundamental interactions of high energy electrons with high-Z materials (targets). When electrons interact with matter, the fraction of the electrons' energy that generates photons increases with the energy of the electrons and with the atomic number of the material with which they interact.

Although photon production is the dominant means by which high-energy electrons lose energy in matter, some energy is manifested in neutron production (chiefly through the giant resonance process), and the generation of other energetic particles as various production thresholds are exceeded. Other radiations may be produced by interactions of high-energy electron beams, but those radiations are produced much less frequently than photons and neutrons. The remaining fraction of the electron energy is deposited in the material as heat.

In general, photon beams produced with electron accelerators have a wide range of energies, but "filtering" with in-beam absorbers narrows the range of energies, thereby resulting in optimum photon beam energies. Attenuation lengths or mass attenuation lengths such as those provided by the Particle Data Group (PDG, 2008) or the National Institute of Standards and Technology (NIST, 2009) are often used to further characterize beam attenuation in material media and thus the fluence rate at each point of interest.

The basic components of an electron accelerator are listed below. Each component has its associated health hazards and, for some components, radiation hazards.

- *electron gun* is the initial source of electrons; a large portion of the current generated by the gun may be lost at the gun exit or in the first portion of the accelerator.
- *klystron tubes (klystrons)* are linear-beam vacuum tubes used to generate and amplify ultra-high frequency electron beams. They employ radiofrequency (RF) power to accelerate electrons in accelerator cavities; electron collectors within klystron tubes require heavy shielding. Klystrons may generate x rays in locations in addition to the collector, requiring additional local shielding. There are other types of RF devices in common use that have characteristics similar to klystron tubes.
- *bending and focusing magnets* are used to steer, focus and control the shape and size of the electron beam at its point of origin. Improper adjustment of the magnet settings may cause beam losses by incorrectly steering the beam into undesirable directions under various abnormal scenarios. Local shielding or collimators may be required.
- *cooling system* usually consists of a closed circuit of deionized water that is typically required to dissipate heat from devices such as beam dumps, magnets, and collimators.
- *vacuum system* consists of vacuum pumps connected to sections of beam pipe. High vacuum minimizes beam losses on residual air and generation of gas bremsstrahlung.

The use of electron accelerators to generate a photon beam is the most mature of the ADT systems in development. With current technology, relatively compact electron accelerators can be built with energies of several tens of million electron volts with average currents of the order of 100 μA and different pulse lengths and repetition rates. The electron beam is aimed at a target generating photons that have a range of energies, with the maximum photon energy equal to that of the electron beam. In addition to filtering the beam with thin in-beam absorbers within the source system, air encountered throughout the beam path will attenuate lower-energy photons in the beam, so the average photon energy in the direct beam will increase with distance from the source. However, the photons that are removed from the beam through attenuation interactions (*e.g.*, scattering) produce a secondary radiation field that increases in area with distance from the source.

As noted above, the photon beam from an electron accelerator is the most mature of the ADT systems in development. A transportable prototype ADT system, PITAS, has been developed and tested at Idaho National Engineering Laboratory. Nominal operating parameters of PITAS are discussed in Section 5.

2.3.2 *Protons*

Proton beams are potential radiation sources for use in ADT systems. A proton accelerator is a viable candidate for use with an ADT system because protons can be produced readily at low energies and have the sufficiently long ranges compared to other nuclear ions. The range data are readily available in scientific literature including the general tabulations of the Particle Data Group (PDG, 2008) and the more specific results in the form of the Stopping and Range of Ions in Materials (SRIM) code (Ziegler *et al*., 1996). Because protons are hadrons (elementary particles that are subject to the strong nuclear interactions, as are neutrons and mesons), when penetrating a material they are attenuated approximately exponentially. As discussed in several of the references (Cossairt, 2009; Cossairt *et al*., 2008; Fasso *et al*, 1990; ICRU, 1978; NCRP, 2003c; Patterson and Thomas, 1973), below 150 MeV the mean free path of protons increases with proton energy. For protons having energies greater than ~150 MeV the mean free path becomes an approximate constant, not strongly dependent upon proton energy and is greater in materials with higher atomic mass number *A*.

A shower of electromagnetic radiation can occur when very high-energy photons interact with matter. This process is called an electronic cascade. Similarly, a shower of hadrons (*i.e.*, neutrons, protons, and mesons) can occur when energetic protons interact with matter. This process is called a hadronic cascade. An energetic proton beam incident on some materials can induce fission due to the interactions of secondary neutrons or neutrons from a hadronic cascade.

Accelerated protons can be used to generate the radiations needed to perform the interrogations intrinsic to ADT systems. While accelerated protons produce fewer photons than accelerated electrons, protons are likely the most effective accelerated particle for producing neutrons, both prompt and delayed, and muons for ADT systems.

The maximum proton kinetic energies achievable with electrostatic systems range from ~1 MeV for Cockcroft-Walton accelerators to ~20 MeV for Van de Graaf accelerators. High power RF systems are needed to achieve higher energies. The technology of such systems is well-known for conventional room temperature applications. Superconducting RF acceleration systems now in use offer certain advantages over room temperature RF systems: reduced electrical power consumption, a better ability to provide continuous wave (CW), rather than pulsed operation, and perhaps smaller physical dimensions. The chief advantage of CW operation is that of increased time that the beam can be produced.

Plausible ADT systems utilizing proton acceleration to produce interrogative neutrons and muons would likely require achievement of kinetic energies in approximately the 0.5 to 10 GeV domain.

2.3.3 *Neutrons*

The use of a proton beam or a deuterium-tritium (D-T) generator is the most plausible method of producing energetic neutrons compared with that possible with electrons or photons. However, the D-T generator is limited to producing only 14 MeV neutrons, thereby limiting its versatility as a source of neutrons in ADT systems. Neutrons produced by a proton beam, before any moderation, could have energies of the same order of magnitude as the primary protons. While accelerator-produced neutrons would be secondary particles of almost certainly lower fluence rates than that of the primary protons, the neutron hazard should be quantified as should the emissions of any fission processes that might result. The neutron hazard, dependent upon both the choice of technology and the configurations of the actual ADT systems could involve both fast and moderated (thermalized) neutrons. If thermal neutrons are involved, the possibility of exothermic thermal neutron capture reactions may be a factor on the necessary hazard assessment. Using neutrons for imaging purposes only is not likely to result in significantly enhanced radiation levels due to secondary particles produced as part of this process, but the design needs to be evaluated for verification of this result.

A proton accelerator used in an ADT system to produce neutrons would consist of an ion source to produce either protons (H+) or negative hydrogen (H–) ions. Following production of the ions, the initial stage of a modern proton accelerator to be utilized for this purpose would likely be a radiofrequency quadrupole (RFQ). While conventional focusing of charged particle beams is typically performed with electrostatic or magnetic quadruple lenses (Cossairt, 2008), RFQs afford the ability to simultaneously accelerate and focus a low energy proton beam (Wangler, 1998). After the first stage of acceleration, the proton beam would be injected into a linac, cyclotron or synchrotron for acceleration to the final desired energy. Once the final energy is reached, the beam would be delivered to and focused on to a target to produce the desired neutrons. The neutron beam would likely be collimated in some manner toward suspected SNM that is the object of the active interrogation to avoid excessive beam spray at large angles relative to the intended direction. In addition, a suitable beam absorber capable of safely handling the proton beam intensity would be needed.

Neutron radiation fields delivered by proton accelerators employed in an ADT system require collimation as they are produced copiously over a wide range of production angles (*i.e.*, the angle between the trajectory of the produced neutron and the incident proton beam). Such collimation would define a specific solid angle of emission that, neglecting absorption and scattering by intervening air, would generate a cone of irradiation with the neutron fluence rate decreasing according to the inverse square law with distance. Absorption and scattering by the intervening air would serve to increase the solid angle of emission and modify the neutron energy spectrum.

In view of the approximate yields of producing neutrons by means of energetic protons interacting in targets (Cossairt, 2009; NCRP, 2003c; Patterson and Thomas, 1973; Thomas and Stevenson, 1988), the achievement of neutron fluence rates up to $\sim 10^{12}$ cm^{-2} s^{-1} would likely require proton beam currents at least of the order 10^{15} s^{-1} (a beam current of ~160 μA), under optimum conditions for producing and collecting the emitted neutrons. This beam current is large enough to be of considerable significance with respect to radiation protection.

2.3.4 *Muons*

Electron beams with energies well above the muon production threshold of 211 MeV are capable of producing pairs of positive- and negative-charged muons. However, by far the most productive way of generating muons is to use protons to produce muons by means of pion (pi meson) decay, and at higher energies and to a lesser degree, kaon (K-meson) production. This method involves the delivery of a proton beam having a kinetic energy well above the pion production threshold of ~140 MeV. Thus the use of either protons or electrons to produce muons requires an accelerator of considerable energy and size.

A proton accelerator is the most logical device for producing a beam of muons in an ADT system. To do this, the most effective method is to create the proton beam and deliver it to a production target typically of low-*Z* such as carbon (graphite) or beryllium oxide. Proton interactions with the target material produce secondary charged pions. If the proton kinetic energy is greater than the kaon production threshold of ~500 MeV, charged kaons could also be produced. Because all of these particles are charged, in contrast with neutron production, electromagnetic fields can be used to focus these charged particles to optimize the profile of the resultant muon beam. The muon beam could then be delivered through air to SNM that is the object of the active interrogation process. The general characteristics of a muon-based ADT system utilizing a high energy proton accelerator as the source of the muons would be very similar to that of a proton accelerator used to produce neutrons except that the proton accelerator for muon production would require the highest possible proton energy in order to produce a sufficient intensity of secondary pions and kaons.

The pions produced by the protons in a muon production mode are then allowed to traverse a region of vacuum (preferred) or air where they are allowed to decay into muons. (Because the corresponding threshold for kaon production is ~500 MeV and the pion production threshold is only ~140 MeV, pionic muon production is always favored over the kaonic process.) Because pions participate in the strong (*i.e.*, nuclear) interaction, a backstop of an optimized thickness would serve to absorb the pions that do not interact while readily allowing penetration by the muons. Muons in this technology have relatively long ionization ranges as their participation in strong interaction processes is, at plausible energies for ADTs, an effect of only minor significance.

For sufficient production of muons, in view of the threshold phenomena involved, the originating proton beam must have a kinetic energy well above 500 MeV to produce sufficient pions to make a potentially usable fluence of muons. If kaon production of muons is to be included, then proton beam energies approximating 1 GeV are required. Production yields of muons due to proton interactions have been provided elsewhere (*e.g.*, Fasso *et al*., 1990). To provide a sufficient fluence rate of muons, a high intensity proton beam is required, likely exceeding the intensity required for neutron generation in a neutron-based ADT system.

For a given ADT installation, the fluence rate of a given muon beam is determined from the relativistic kinematics of the production process along with the arrangement of shielding, pion absorbers, and any magnetic fields present. The long ionization range of muons is likely to be employed by future ADT systems, perhaps principally to produce muonic atoms in high-*Z* materials. Some values of ionization range as a function of energy are given by NCRP (2003c), Particle Data Group (PDG, 2008), and Sullivan (1992). For the energy domain of likely interest for use in the technology of ADT systems, Barkas and Berger (1964) give a detailed set of results for both muon stopping powers and ranges.

A plausible additional application of muons in ADT systems is the emission of muonic x rays by muons in atomic quantum states. Such x rays would give a unique energy signature of high-*Z* materials in this particular active interrogation scheme. To do this would require the energy of the interrogating muons to be adjusted so that they are stopped, presumably by ionization, in the material of interest.

The physical size and general characteristics of the proton accelerator used to produce the muons is similar to that anticipated for neutron production. The main difference is the requirement to include the region needed to focus the pions and kaons, and allow for their decay to the resulting muons. The dimensions of such a decay region are not small in view of the fact that the length traversed by these particles must take into account the finite mean-lives of the moving parent pions and kaons as measured in the laboratory frame of rest. While the muons produced in this manner have a greater intensity in the direction of the incident pion and kaon beams, it is plausible that focusing of the muons using magnetic devices beyond the decay region would be needed to further optimize a muon beam. Furthermore, in addition to the beam absorber needed to handle the primary proton beam, the pions and kaons would need to be disposed of in either the same beam absorber as that used for the protons or in a separate device.

3. Optimization of Active Detection Technology Systems

The success of any ADT system depends on a careful balance between the source output and its associated detection system. The strongest source emission achievable will yield useless results if the emission is not matched to an appropriate detector located an acceptable distance from SNM. Likewise, the most capable detection system available will simply register events resulting from natural background radiation if a suitable source emission is not employed.

The solution to the balance issue can be approached in one of two manners: forward approach (based on source capabilities) or the reverse approach (based on detector capabilities). Each of these approaches is predicated upon the output of a certain ADT system (forward) or the capabilities of a specific detector (reverse). Regardless of the technique chosen, the process will likely require an iterative approach to adequately balance the source emission strength, detector capabilities, and the desired standoff distances.

3.1 Forward Approach Based on the Source Requirements

In the forward approach, one uses a viable source emission strength along with a knowledge of the source-to-SNM and SNM-to-detector standoff distances to evaluate the ability of a radiation detector to distinguish the resultant radiation signature. The adequacy of the detector can be evaluated by calculating the particle flux at the detector using the relation:

$$\phi_{\mathrm{D}} = K\, S(\Omega)\left(\frac{d\Omega}{dA}\right)F(\Omega)\;\Delta\Omega_{\mathrm{SNM}\rightarrow\mathrm{D}}, \tag{3.1}$$

where:

K	=	accounts for the attenuation of all particles in air (source-to-SNM and SNM-to-detector) and in shielding
$S(\Omega)$	=	angular source distribution from the interrogating beam
$d\Omega/dA$	=	corrects for differences between the solid angle and spherical coordinates
$F(\Omega)$	=	angular source distribution resulting from the interrogation of SNM
$\Delta\Omega_{\mathrm{SNM}\rightarrow\mathrm{D}}$	=	fractional solid angle subtended by the detector at the centerline of SNM-to-detector standoff distance (Evans, 1982)

It should be noted that there will be significant variances in the K term for use in a mobile platform due to the movement of the source and SNM.

For a point source interrogation beam creating an isotropic signal (photofission, etc.) within SNM, Equation 3.1 becomes:

$$\phi_{\mathrm{D}} = K\left(\frac{S_{\mathrm{o}}}{4\pi}\right)\left(\frac{1}{R_1^2}\right)\left(\frac{F_o}{4\pi}\right)\left(\frac{A_{\mathrm{D}}}{R_2^2}\right), \tag{3.2}$$

where:

S_0	=	number of particles per second emitted by the ADT system
R_1	=	centerline distance from the ADT system to SNM
A_{D}	=	effective detector area
R_2	=	centerline distance from SNM to the detector

Note that if a monostatic (same location) source and detector is employed Equation 3.2 can be reduced to:

$$\phi_{\mathrm{D}} = K \left(\frac{S_o F_o}{16\pi^2}\right)\left(\frac{A_{\mathrm{D}}}{R_2^4}\right), \tag{3.3}$$

If the particle flux calculated in this manner is acceptable, no additional consideration needs to be taken into account. However, if the flux is inadequate, one or more of the following actions must be taken: reduce the standoff distances; increase the source emission strength within the confines of the dose limits; or increase the size of the detector. If the detector is not colocated with the ADT system, the standoff distances may be altered independently to achieve an acceptable detector flux.

3.2 Reverse Approach Based on the Detector Requirements

If the reverse approach is employed, one begins with an acceptable particle flux for a given detector and standoff distances, then solves Equation 3.1 or 3.2 for the necessary source emission characteristic (S_0). If the ADT system is capable of producing the required S_0, no further analyses need be performed; however, if the required S_0 is greater than the maximum output of the ADT system, the standoff distances must be decreased. As was the case with the forward approach, the standoff distances can be adjusted independently if a monostatic system is not utilized.

3.3 Radiation Detection

3.3.1 *Detector Types*

The selection of the detector will be controlled by the choice of the interrogating radiation type and energy because these parameters will determine the prompt emissions escaping from SNM. In general, prompt photon emissions will always be induced in SNM regardless of the incident radiation and type; however, proton and neutron beams can also produce fission in fissionable or fissile material, resulting in neutron emissions.

3.3.1.1 *Ideal Detectors.* Regardless of the type of interrogating radiation that is used, the ideal detector for this application will possess the best overall combination of the following important characteristics:

- intrinsic efficiency (sensitivity);
- obtainable geometries;
- response time;
- signal-to-noise ratio;
- availability;
- versatility; and
- cost.

A high intrinsic efficiency will allow for greater standoff distances between SNM and detector and a fast response time will ensure that emission from SNM can be quickly processed. Materials that can be readily molded into or produced in desired geometries provide users with a large degree of freedom in designing specific detection platforms. Detectors that have dual-use application for neutrons and photons should always be considered, since they offer the user the flexibility to use more than one type of interrogating radiation. However, no detector material, regardless of its merits, should be considered if supplies are dwindling and will be unavailable in a short period of time.

There are many detector materials that provide superior intrinsic efficiencies for either photons or neutrons; however, these materials are generally only available at a significant cost and with a low versatility. These materials also generally have response times that are relatively slow and they are not usually available in customizable geometries. Liquid and plastic scintillators, on the other hand, do not provide the highest intrinsic efficiencies for photon detection. However, they provide excellent detection efficiencies for neutron emissions, they are relatively inexpensive, can be molded into custom volumes specific to the user and have very fast response times. In addition to the aforementioned advantages, liquid and plastic scintillators can be loaded with chemically-compatible materials, such as lead, tin, gadolinium and boron to improve the photon detection efficiency of the base material. These organic scintillators also possess superior pulse shape discrimination capabilities that allow them to discriminate between photons and neutrons. Consequently, the organic scintillators, unlike all the other detector media, can serve as dual monitors for both types of radiations. For all these reasons, liquid and plastic scintillators should be given a great deal of consideration when selecting a detector medium for an ADT system utilizing photon beams.

ADT systems using muon beams are quickly gaining popularity as candidates for SNM detection because these beams will penetrate much farther into shielding material and the stopping of a muon within SNM produces highly-energetic x rays that are isotope specific (Close *et al*., 1978; NCRP, 2003c) and therefore, this system should be coupled with some type of inorganic crystalline detector such as high-purity germanium (HPGe), sodium-iodide (NaI), cadmium-zinc telluride (CZT), or cadmium telluride (CdTe) that will provide a suitable detection efficiency. The output of the crystalline detectors should also be processed through a multi-channel analyzer (MCA) to provide for an accurate identification of isotopes in SNM (Stocki, 2010).

3.3.1.2 *Available Detectors.* There are a wide range of detector media available for neutron and photon monitoring, such as gases (*e.g.*, ^{3}He and $^{10}BF_3$), inorganic crystals (*e.g.*, HPGe, NaI, CZT, CdTe), and organic scintillators (liquids and plastics). In large measure, the choice of a detector will depend upon the detection efficiency along with the response time; however, the availability of the media is an important consideration as well. Of the available detector media, ^{3}He and isotopes of lithium and gadolinium have limited supplies.

3.3.2 *Detection Efficiency*

The detector can affect radiation measurements in two main manners. First, the housing covering the sensitive volume may attenuate or absorb the particles that have been scattered into the solid angle encompassing the detector. Second, even if the radiation penetrates the housing, it may pass completely through the medium without interaction or it may deposit energy up to, and including, the full energy of the incident radiation (Tsoulfanidis, 1995). For the purposes of this

Commentary, it is assumed that the first mechanism is negligible, leaving the second mechanism, or detector efficiency as the main consideration.

Detector efficiency can be quantified as either absolute or intrinsic. Absolute efficiency (ε_{abs}) is given by:

$$\varepsilon_{abs} = \frac{\text{number of particles recorded per unit time}}{\text{number of particles emitted by the source per unit time}}. \tag{3.4}$$

This quantity is very useful when attempting to determine the activity of a source based on the detector measurements. However, since the ADT system is designed to produce secondary particles through various radiation interactions within SNM and the solid angle associated with these interactions is accounted for in Equations 3.1 to 3.3, the more appropriate quantity for consideration here is the intrinsic efficiency (ε_{int}). This quantity is defined as:

$$\varepsilon_{int} = \frac{\text{number of particles recorded per unit time}}{\text{number of particles incident upon the detector per unit time}}. \tag{3.5}$$

The intrinsic efficiency for a particular detector is dependent upon the: detector material, radiation type and energy, thickness of the detector in the direction of the incident radiation, and electronics associated with the detection system (Knoll, 2000; Tsoulfanidis, 1995).

3.3.2.1 *Intrinsic Efficiency.* The intrinsic efficiency of a detector will increase if a detector material is chosen such that there is a greater probability of interaction with the incident radiation. The density of solids or liquids is at least three orders of magnitude greater than that of a gas; therefore, the use of these materials in the detector will significantly enhance the intrinsic efficiency. However, the detector material must also be tailored to the radiation type being monitored.

For the purposes of this Commentary, it is assumed that the radiation type will be either a photon or a neutron. Photon interactions are more probable in materials with a high-Z; however, neutrons, on the other hand, are largely only scattered elastically by high-Z materials and are more effectively attenuated by materials having a large hydrogen component. Unlike charged particles, which can be completely stopped by ionization processes in the detector volume, neutrons and photons can travel great distances in the various media and are attenuated in a generally exponential manner. Therefore, there is always a non-zero probability that these radiation types will pass through any thickness of material without interaction, which means that the intrinsic efficiency of a neutron or photon detector will always be <100 %.

The thickness of a particular material will also have an effect on the intrinsic efficiency in a similar manner as does the density. By placing longer lengths of material in the path of the incident radiation, the probability of interaction is increased, which likewise increases the likelihood of detectable pulses being measured.

Systems using some type of discrimination (*e.g.*, pulse shape discrimination or pulse height discrimination) can indirectly affect the intrinsic efficiency. If a pulse is produced in the detector that does not conform to the discrimination settings of the electronics, it will be rejected, resulting in a decrease in the intrinsic efficiency. However, this effect can be reduced in large measure by reducing the system noise, thereby allowing for a lower threshold setting which will minimize the number of rejected interactions and improve the intrinsic efficiency.

3.3.2.2 *Signal-to-Noise Considerations.* Radiation measurements always contain a certain degree of error that is either associated with the system itself or due to random fluctuations that are commonly referred to as noise. The system error refers to the situation where each individual measurement can fluctuate about a mean value (below or above), while the noise results from several different mechanisms. In many instances, the largest components of noise are dependent on the detector type. For example, noise in scintillation detectors results, in part, from variations in light intensities, which are totally irrelevant for gas-filled systems. However, apart from system-specific considerations, noise is generally caused by the detection system, microphonics, and random fluctuations in the natural background radiation level.

Noise within the detection system can result from any of the various components that are used to process the radiation-induced signals, such as photomultiplier tubes, preamplifiers, resistors, and capacitors. This type of noise is often referred to as Johnson noise or white noise because the frequency spectrum is very broad and is often considered to be relatively uniform. Additional detector noise can be introduced by the type of pulse shaping that is performed on the electrical signals.

Microphonic noise can result from mechanical vibrations that are introduced into the detector or into the preamplifier stage of the detector electronics. The mechanism for the introduction of this noise is the small movement of electrical components within the detector that cause capacitance changes and give rise to spurious signals. Even a small change in the capacitance (10^{-7} pF) can produce an electrical pulse equivalent to that resulting from the deposition of several kiloelectron volts of radiation energy. For mobile or nonstationary systems, this noise presents serious problems because it degrades the energy resolution and produces spurious energy peaks on spectroscopy systems and produces spurious pulses on counting systems. Microphonic noise can generally be reduced through dampening agents, collars or sleeves around signal leads, or analog shaping using band pass filters. However, if the noise remains and is within the frequency range of the detector signals, more sophisticated methods such as digital waveform processing must be used (Uritani *et al*., 1994).

Nothing can generally be done to reduce or stabilize the amount of natural background radiation present for nonstationary radiation detectors. The user must simply account for the presence of signals arising from the environment. However, the use of an ADT system will also produce an additional source of background radiation because the interrogating particles will not only produce fission in SNM, but also secondary radiations in surrounding materials such as steel and lead that will be present on ships or other structures. These resulting particles must somehow be distinguished from those created within SNM alone.

3.4 Deployment Considerations

The ADT system is likely to be deployed in various mobile configurations such as ships and land vehicles. The use of mobile platforms allows these systems to be deployed well outside population centers and, coupled with sensitive radiation detectors, allows for a significantly expanded field of view. However, the nonstationary nature of these platforms also creates challenges for keeping the interrogating beam on-target, while ensuring that the entire surface area of SNM has been interrogated.

3.4.1 *Energy Source*

Depending on the signal to be generated (continuous or pulsed), the detector and energy source may need to be accurately triggered to ensure that the signal is properly evaluated. The size and weight of the energy source that is required for the ADT system will dictate acceptable deployable platforms.

3.4.2 *Environment*

Since the ADT system and its associated detectors are to be deployed in various mobile configurations (sea, air, land), each component needs to be capable of operating under the adverse weather and environmental conditions that are expected in the course of the system's normal use. The system must be weather-proof and evaluated for acceptable operating ranges of humidity, temperature, RF interference, etc. as required by all applicable standards of the American National Standards Institute (ANSI).

4. Radiation Protection Framework

4.1 Radiation Protection Program Goals

NCRP Commentary No. 21 (NCRP, 2011) provided recommendations for the application of fundamental principles of radiation protection to ADT systems and radiation protection goals and philosophy for such systems. The ADT system radiation protection goals should be designed to be consistent with those of NCRP, namely to prevent the occurrence of deterministic effects and limit the risk of stochastic effects (*i.e.*, cancer and genetic effects) to a reasonable level in relation to societal needs, values, benefits gained, and economic factors (NCRP, 1993).

The principles underlying the NCRP system of radiation protection (NCRP, 1993) are the need to:

- justify any activity that involves radiation exposure on the basis that the expected benefits to society exceed the overall societal cost;
- ensure that the total societal detriment from such justifiable activities or practices is maintained as low as reasonably achievable (ALARA), economic and social factors being taken into account; and
- apply individual dose limits to ensure that the procedures of justification and ALARA do not result in persons or groups of persons exceeding levels of acceptable risk.

This Commentary provides recommendations for technical considerations in the design of ADT systems that would allow achievement of the radiation protection program goals and dose limits detailed in Commentary No. 21 (NCRP, 2011).

Consideration of the low visibility use of the system will impact the ability to implement the dose limits for potentially exposed persons. ADT systems are intended to be used in much less controlled environments than existing human and cargo screening systems. In addition, areas immediately adjacent to the primary beam and behind SNM may experience elevated dose rates and be difficult to control.

4.2 Dose Limits

NCRP has developed different recommended dose limits for occupationally exposed workers and for members of the public (NCRP, 1993).

4.2.1 *Occupational Exposures*

NCRP (1993) recommends that the cumulative lifetime effective dose of occupationally exposed workers be limited to 10 mSv times the age of the individual in years, with an annual effective dose limit of 50 mSv. Pregnant occupationally exposed women should be limited to an equivalent dose to the embryo and fetus of 0.5 mSv per month.

4.2.2 *Exposures to Members of the Public*

NCRP (1993) recommends that continuous exposure of members of the public be limited to an annual effective dose of 1 mSv. For persons exposed infrequently, NCRP recommends an annual effective dose limit of 5 mSv. Exposure to a single source under one control should be constrained to 0.25 mSv annually (NCRP, 1993). These limits exclude exposures from natural background radiation and radiation exposure associated with medical diagnosis and treatment. For comparison, the average annual exposure to natural background radiation is 3.1 mSv, and the average annual exposure from sources associated with medical diagnosis and treatment is 3 mSv (NCRP, 2009).

4.3 Dose Limits for Active Detection Technology Systems

Upon consideration of the intended use of the ADT systems, NCRP Commentary No. 21 (NCRP, 2011) recommends that the effective dose to a non-occupationally exposed individual from the use of the ADT system not exceed 5 mSv (NCRP, 2011). This limit applies to the total dose an individual might receive during an inspection event, taking into consideration the low probability that an individual might receive multiple exposures as a result of repeated events. This dose limit is consistent with the NCRP recognition that exceptions to the 1 mSv y^{-1} public dose limit (Section 4.2.2) for prolonged or repeated exposures might be justified in some circumstances on the basis of infrequent exposure or significant benefit to those exposed or to society as a whole.

Persons who might be exposed to ionizing radiation from the use of ADT systems include the following groups:

1. Participants involved in the operation of the ADT system. These persons would presumably be informed of the potential radiation doses near the device or in the path of its beams and would be advised about the appropriate precautions.
2. Bystanders outside the area being inspected and who are not involved in the operation of the ADT system, but might be exposed to radiation. These could include military or civilian personnel, distinguished from Group 1 by being unaware that they may be exposed to ionizing radiation from the ADT system.
3. Persons in the area being inspected, unaware of the radiation, and not knowingly involved with the transport of SNM.
4. Persons in the area being inspected who are knowingly engaged in the transport of SNM, but not aware that they may be exposed to radiation.

Dose limits for Group 1 would be those for occupational exposure; for Groups 2 and 3, the limits would be those for members of the public. It could be argued that persons in Group 4 are enemy combatants and could justifiably receive radiation doses higher than members of the public, even though unaware of the specific doses. Further discussion of the dose limits for enemy combatants is beyond the scope of this Commentary and is not addressed.

The limit of 5 mSv per inspection event with the ADT systems is also consistent with prior NCRP recommendations for infrequent exposures to the public through use of other ionizing radiation-based systems for scanning cargo for nuclear materials or other contraband

(NCRP, 2003b; 2007). Infrequent exposures are discussed in NCRP Statement No. 10 (NCRP, 2004), and are defined as follows:

> "On an infrequent basis, a member of the public may receive more than 1 mSv y^{-1}. In such a case, the annual effective dose may exceed 1 mSv up to a value of 5 mSv. This Statement recommends that the term "infrequent," in the context used here, should refer to a justified exposure that is not likely to occur often in an individual's lifetime, with each occurrence justified independently of any other."

Two potential inspection scenarios are considered; the maritime and the land inspection scenarios. For both scenarios, it is assumed that the suspect vehicle would be inspected in such a manner that interrogation radiation would have minimal interaction with other transport vehicles or persons in the area. Radiation protection controls, both engineered and administrative, should be instituted to maintain doses below 5 mSv per inspection event. These are discussed further in Section 6.

4.4 Ethical and Public Policy Issues

The purpose of the use of the proposed ADT systems is to determine if SNM is being transported in a container, presumably by land or by sea. For purposes of this discussion, NCRP assumes that there would be minimal to no interaction with other vehicles or persons in the area.

If the detection technology were a digital camera with a telephoto lens, there would be no serious ethical issues. But ADT systems involve ionizing radiation emitted by the interrogation device and possibly from the reflections from nuclear materials that are being investigated, raising the possibility that humans might inadvertently be exposed to that radiation.

The intention is to design and operate the system in a way that would limit human exposure, even if inadvertent. Because it will not be possible to ensure that humans are not exposed, the possibility of harm exists. The likelihood and severity of harm, and whether it can be avoided, is uncertain, and is a major subject of this Commentary.

Because there is a universally recognized duty not to cause serious harm to innocent individuals, the development and deployment of ADTs, if they involve more than trivial doses to humans, raise ethical questions about whether the justifications for use of such a system is sufficient to warrant the radiation dose. In addition to questions about the commensurability of benefits and risks, higher doses would raise questions of consent from persons potentially exposed to ionizing radiation from ADT systems, and accountability for the use of the device.

4.4.1 *Benefit-Risk Considerations*

As a general matter, benefits should outweigh the risk of harm. If, for example, there were a very high potential benefit of using the ADT system (*e.g.*, a potential explosive device in a highly suspicious container), exposing individuals to higher radiation doses from use of the ADT system might be justified. Conversely, interrogating containers that have a low probability of containing SNM would confer a low probability of benefit, and would only be appropriate to use if the ADT system presented a low probability of human exposure.

There is some possibility of radiation exposure from nearly all technologies involving the use of ionizing radiation, so reduction of radiation doses to zero is generally not practical. Obviously, all reasonable efforts to minimize radiation doses should be taken. For example, if a person were to inadvertently cross the path of a beam between the ADT source and the interrogated object, the beam might need to be interrupted automatically before the person receives a significant dose. Similarly, the intensity of the beam should be as low as possible, consistent with achieving its purpose.

The requirement that benefits outweigh potential risks calls for a high level of confidence that the device will produce meaningful information. If, for example, the system had low sensitivity or specificity (with a high rate of false positive or false negative results) it would be more difficult to justify exposing persons to even low doses.

Similarly, if there were significant risk, the reasons for interrogating a specific container should be substantial. The scenarios considered were limited to containers that were suspected of containing SNM based on prior information. If the use of the ADT system were expanded to perform random surveillance of a large number of containers, with low probability of containing SNM, the potential benefit from each use would be less, and the benefit-risk ratio would decrease.

Finally, if the ADT involves potentially radiation doses greater than the dose limit, there should be assurance that there are not safer alternative methods of detecting SNM. Whether or not the increase in radiation doses is justified depends, in part, on the cost, efficiency, and radiation doses from other inspection techniques. The assumption that a technologic method is superior to human activity is often assumed without adequate examination.

4.4.2 *Consent and Accountability*

Consent can justify exposing persons to ionizing radiation, with its attendant health risks. Thus, it is appropriate to expose radiation workers to higher radiation doses than members of the public, because the workers may choose to receive higher doses in exchange for the benefits of employment, and can be alerted to take precautions to reduce their exposure. NCRP assumes that operators of the ADT would be fully aware of the potential radiation doses, and their doses would be minimized by the design of the device.

More complicated questions arise if unknowing persons might be exposed to ionizing radiation from ADT systems. As noted previously, NCRP assumes that there will be minimal to no interaction with other vehicles or persons in the area; the word “minimal” suggests that it is not implausible that there would be human exposure.

NCRP considered, for example, the possibility that an enemy combatant, or even an innocent civilian, might be close to the inspected object, outside of the awareness of U.S. agents employing the device. NCRP also considered the possibility that civilian dockworkers might be directly between the ADT source and the inspected object. Based on information presented to NCRP, it appeared that the intent is that a single exposure would involve a negligible radiation dose (*i.e.*, comparable to the natural background radiation dose encountered in ordinary life).

The assumptions of low or trivial radiation doses might be invalid if the device were used in different scenarios (*e.g.*, multiple interrogations of containers moving in and out of a port on a daily basis) whereby an individual (*e.g.*, dock worker) might have multiple exposures with a cumulative dose that would be nontrivial.

If there were a plausible risk of significant harm, particularly to bystanders near the ADT system, consent might take different forms. If the health risk were low but plausible, it would probably be sufficient to rely on implied consent, with general information provided to the class of persons at risk, so that they could choose to opt out of working in that environment. For security reasons alone, it would not be practical to inform bystanders of specific details about the deployment of the device.

There is also a question of whether there should be general consent by the public, whether through the democratic process of legislative and regulatory approvals for development and deployment of such devices; through general information programs by the government; or the free flow of information to the mass media. It is unclear to whether the deployment of ADT systems (as a general matter, not specific information about exact sites) would be public information. To the degree that general awareness of the system would not interfere with its effectiveness, openness is preferable to secrecy.

There is an issue about whether the device would have any deterrent value, in which case its general deployment would be widely known. It is also unclear whether the owners or operators of suspected vehicles would be informed or aware that the vehicle was being inspected

(*e.g.*, whether trucks would be inspected with or without the consent and awareness of the driver.)

Whether or not public consent, or at least acquiescence, should be required is in part related to the degree of risk, but also to the perception of risk, as fear can be unrelated to actual risk. Recent discussions of enhancing examinations of airport passengers with more invasive scanning devices suggests the public is generally tolerant of minimal health risks of radiation if they provide a substantial decrease in the risk of harm from terrorists.

Consideration should be given to the development of ADT systems, apart from questions about deployment once the system is operational. Once again, the magnitude of potential radiation doses plays an important role. If the radiation doses from use of ADT systems were trivial under all plausible scenarios, there would be little reason for public discussion. But if there were potential radiation doses exceeding the dose limits, questions about development might be important in a democratic society.

Finally, questions of accountability arise if there are potential radiation doses exceeding the dose limits. If the radiation doses to individuals from an ADT system are substantially above the recommended dose limits, those responsible should be held accountable. If the radiation doses are trivial, then questions about deployment might be appropriately made at a lower level, but in any case it should be clear as to who is authorized to deploy the device in a specific location. If it were deployed in a foreign country, there would generally be an obligation to obtain the permission of an appropriate representative of that government.

4.4.3 *Expansive Uses of the Technology*

Many of the most controversial issues surrounding new technologies arise when they are used for purposes not intended or anticipated in their early stages. Mechanical ventilators, for example, were developed for brief support of post-operative patients, but are now widely used to prolong life indefinitely for many patients with little or no prospect of meaningful recovery. Exploration of space for scientific reasons has wide support, but its expansion to military use would be more controversial.

One obvious use of ADT technology would be as part of an offensive weapon system. NCRP received no information suggesting that ADT technology was being developed for offensive purposes. Nonetheless, the potential transfer from its use as an interrogation device to its use for the purpose of injuring or killing persons exists; it is important for the public to be assured that the intended purpose of ADT technology is as described.

5. Exposure Scenarios

As stated previously, the use of ADTs may expose bystanders. Because the range of operational capabilities of the proposed ADT systems is unknown at this time, it is not clear what radiation levels would be required for effective detection of nuclear materials and hence what levels of radiation might be involved in unintended exposures to members of the public. Information about these levels will be needed for the appropriate application of the principles of justification and ALARA. The ADT systems will likely be deployed in the field with a wide range of possible operating scenarios and conditions presenting an equally wide range of possibilities for inadvertent exposure of members of the public.

Determining the doses that would be received by exposed individuals relative to the dose limits recommended for workers and for the public as developed by NCRP (2011) clearly presents a significant challenge regarding the proposed ADT systems. In the absence of specific information about the design or performance of such systems, a framework that is based on generalized exposure scenarios and exposure zones is provided to allow for discussion. Earlier NCRP commentaries have evaluated emerging technologies for homeland security applications and developed guidelines for their usage. However, in all these earlier cases the technologies were well defined and expected to be deployed in fixed facilities with tightly controlled access to the irradiated area. The proposed ADT systems are fundamentally different in so far as they are not yet fully developed and may be deployed in uncontrolled environments where the extent of the irradiated area is likely to be much larger and the ability to control access to such areas will be greatly diminished.

In the following section the general design criteria for ADTs as set forth by DTRA are described and a number of potential exposure scenarios reviewed for the purpose of identifying potential exposure zones and types of potentially exposed individual during operation of these devices.

5.1 DTRA General Scenario Descriptions for ADT Systems

In 2008, DTRA issued a Broad Agency Announcement (BAA) that called for development of new standoff detection technologies (DTRA, 2008). This BAA set forth the requirement that there be a minimum of 100 m standoff between the interrogating device (and operators) and the object with a minimum distance from object to detector of 50 m. The expectation was that the equipment would be operable outdoors from sea level to 1,500 m elevation under a broad range of humidity and temperatures. Equipment may be operated on land or marine platforms under a number of possible environmental conditions such as the inherent motion of the platform for a ship at sea, and sea spray.

While some radiation dose is associated with radiation generating devices such as ADT systems, the intention is to design and use the systems in a way that would keep radiation doses below the dose limits for operating personnel, bystanders, and individuals in the inspected areas. ADT systems use radiation to stimulate detectable signatures from fissile threat materials. The possible radiation types include high-intensity bremsstrahlung radiation and particulate radiations including neutrons, protons and muons. The interrogation types are discussed in more specific detail in Section 2.3. The resulting signatures include prompt and delayed neutron and gamma emissions from induced fission events, x rays from muon interactions with high-*Z* materials, and other signatures resulting from particulate or electromagnetic radiation interactions with SNM and other potential radiological weapons materials. The stimulated signatures would facilitate long-range detection of the threat materials using detectors that are spatially and temporally linked to the ADT system sources.

This Commentary considers several of the most plausible ADT systems, focusing on the source of ADT radiation and the potential secondary sources generated through ADT system usage. Currently, the accelerator-based radiation sources represent those ADT system types in the most advanced stages of research and development and pilot testing. Proton accelerators and electron accelerators are likely the best sources of such secondary radiations (photons, muons, neutrons) with sufficient energy and fluence rate to accomplish the goals of ADT systems.

5.2 Potential ADT System Exposure Zones

ADT systems have the potential to produce very high instantaneous or pulse dose rates depending upon system parameters, system operation, and location of the person. In particular, it is vital to consider all individuals who might receive direct exposure to the beam between the device and the inspected area. However, it is important that all potentially exposed individuals are considered including operating personnel, bystanders, and individuals in the inspected areas. To ensure that a comprehensive evaluation is made, it is helpful to consider the different locations where exposures may occur. This requires a systematic evaluation of the specific ADT system to be deployed, the sources of direct and secondary irradiation, and potential interactions with the different materials in the irradiated environment.

Potential applications of ADTs identified include detection at a distance along transit routes and in distant vehicles or aboard ships at sea, in facilities in an inaccessible territory, or in a city (Medalia, 2009). The numerous cargo containers imported into the United States daily (NCRP, 2011) represent another potential application. These operations might require scanning of large areas to locate material or rapid data acquisition if the material is moving quickly across a detection field. As noted previously, maritime and port-based exposure scenarios are considered. In the maritime scenario, operators are likely positioned on the interrogating ship (or platform), the beam is shot from the interrogating ship to the possible nuclear material on the interrogated (or inspected) vessel at some standoff distance. There is both sea and land behind the interrogated vessel, as well as open water outside of the beam area. Each of these locations represents a possible exposure area. In the port-based scenario, the operators are located in a fixed position on land (in or close to the port) from which the beam is shot to the possible nuclear material on the interrogated vessel as it travels in the shipping lane past the inspection location. There is water behind the interrogated vessel and possibly land or other vessels. Outside of the beam area there is open water, and there may be other vessels or structures such as bridges.

A simplified and generalized exposure zone concept is shown in Figure 5.1, where letters A to E designate specific exposure zones. Descriptions of these zones as well as the likely types of exposed individual in the area and a brief description of radiation sources in each zone are included in the paragraph sections below. Additional detail on ADT radiation sources is addressed in Section 5.1.

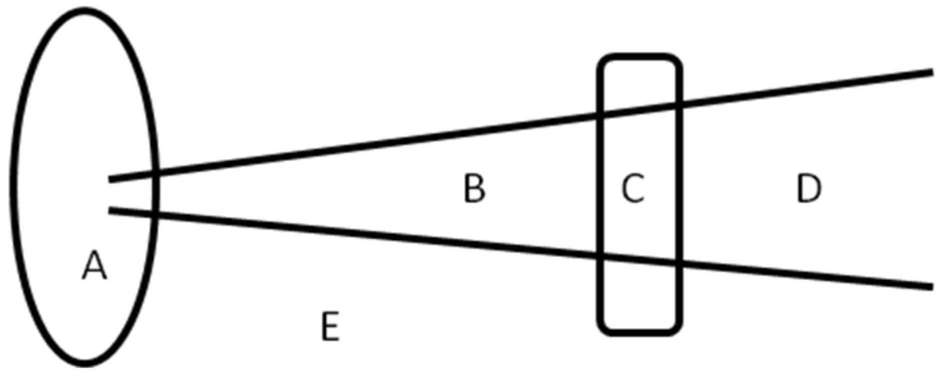

Fig. 5.1. Generalized exposure zone designations.

5.2.1 *Exposure Zone A: Operational Zone*

- *Zone description*: The operational zone represents the area of likely exposure related to the operation of the interrogating aspects of an ADT system. This zone includes all areas where the ADT beam generating device exists, such as a ship, platform or vehicle. In the design of these systems, the detectors can either be collocated with the interrogation source or they can be on a separate platform. The latter option might permit detection from distributed sensors, from ships or trucks, or unmanned aerial or underwater vehicles.
- *Likely-exposed individuals*: Individuals likely to be located in this zone and therefore potentially exposed include operators of the ADT equipment, operators of the interrogating ship, platform or truck, and any other individuals associated with the device and its deployment. All these exposures would be considered occupational since they would be part of the action to deploy and operate the ADT system.
- *Dose sources in this zone*: Doses in the operational zone will result from exposures to scattered beam, secondary radiations produced through bending or scattering phenomena, as well as from direct beam. In addition, doses could result from the decay of activation products produced in the beam shield and device construction materials. The magnitude of the dose will depend on a variety of factors including the degree of shielding for the ADT system, proximity to the dose sources and the time period and frequency on which the beam operates. It is anticipated that the magnitude of these doses can be well defined during the development and testing phases of the ADT system so that measures can be taken to reduce them to a minimum.
- *Specific zone considerations*: Operators of the system will require specific system-based training in order to minimize doses in this zone.

5.2.2 *Exposure Zone B: Direct Beam Pathway*

- *Zone description*: The direct beam pathway includes the area between the beam source and the object that is irradiated by the beam. The extent of this zone will depend on the distance between the beam source and the object, and the change in beam width with distance. These characteristics will depend not only on the ADT system used but also the environment in which it is operated.
- *Likely-exposed individuals*: Any individual located within Zone B when the beam is operated will be exposed. Furthermore, the very nature of the application precludes establishing physical control of this zone to exclude the presence of such individuals. Ideally the ADT will be designed so that the beam will not operate if a person is located within this zone. This requires the ability to detect individuals entering the area and the ability to automatically turn the beam off.
- *Dose sources in this zone*: The interrogating beam is the primary source of dose to any individual crossing its path. Furthermore, the interaction of primary and secondary particles in the beam with nuclei in the air, dust, and any other environmental media may result in activation products. For this reason every effort should be made to avoid the presence of vegetation, physical structures, and biota occurring in the line of sight from the beam source to the object. Again, the magnitude of these doses under a realistic range of field conditions can be established during the development and testing phases.
- *Specific zone considerations*: The expected distance between ADT systems and the objects for inspection might make it impossible to limit access to the irradiated zone

and might lead to radiation levels to accidentally exposed individuals near the device that are much higher than those associated with the other security systems NCRP has considered previously.

5.2.3 *Exposure Zone C: Inspected Area Zone*

- *Zone description*: The inspected area represents the area of likely exposure at the object location related to the operation of the interrogating aspects of the ADT system. This zone is potentially large as it includes all the areas associated with the object location which may be a ship, vehicle, structure or container. The size of the inspected area will be influenced by the beam width at the object, and the mode of interrogation which could be localized or continuous if it is used to scan a large area. The latter aspects will determine the duration of exposure.
- *Likely-exposed individuals*: Individuals likely to be located in this zone and therefore potentially exposed will depend on the characteristics of the inspected area and the methodology of scan. If the inspected area is moving, such as a ship or vehicle, operators of the inspected ship, etc., and any other individuals associated with the inspected area may be exposed. If the methodology of scan includes a sweeping scan beam, operators and any other individuals associated with the inspected area may also be exposed at some point during the scan. Essentially any individual in the vicinity of the interrogated object may be exposed.
- *Dose sources in this zone*: Three potential sources of dose can be identified in this zone: direct irradiation by the interrogating beam, exposure to secondary radiations produced from interrogation of SNM, and irradiation from materials activated by the

interrogating beam in this zone. The magnitude of the exposures will also depend on the scan methodology, radiation type and energy, and the exposure duration.

- *Specific zone considerations*: The remote interrogation of the object area make it impossible to limit access to the irradiated zone and might lead to radiation levels to inadvertently exposed individuals near the device that are much higher than those associated with the other security systems NCRP has considered.

5.2.4 *Exposure Zone D: Beyond Inspected Area Zone*

- *Zone description*: The area beyond the inspected zone represents an area of potential exposure related to operation of the ADT system. The extent of this area will depend on a range of factors including the beam intensity and duration; the characteristics of Zone C both with regard to ability to attenuate the beam and serve as a source of secondary radiation; and the characteristics of the environment beyond the object location. It will be very difficult to control access to this zone.
- *Likely-exposed individuals*: Any individuals present in this zone may be exposed inadvertently and exposures will depend on the details of the scenario where the ADT system is used. For the maritime scenario, a separate ship from the target ship would have to be located in this zone for individuals to be exposed. In contrast, individuals would have to be located on the far bank or in a separate vessel in the port scenario. Although physical control of this zone is impossible, active surveillance of the location and movement of vessels in the general vicinity of operations is essential to avoid such exposures.

- *Dose sources in this zone*: Doses to exposed individuals would result from direct exposure to the interrogating beam as it travels beyond the object location. Exposures may also result from secondary radiation generated from interactions at the object location that potentially extend to Zone D; or from secondary radiation produced from interactions with the surrounding environmental media.
- *Specific zone considerations*: The duration and frequency of use of an ADT system at any particular location would have to be evaluated to determine the potential for the accumulation of longer lived activation products and exposure to them.

5.2.5 *Exposure Zone E : Outside Beam Bystander Zone*

- *Zone description*: The bystander zone outside the beam path and between the beam source and interrogation object represents an area of potential exposure related to the operation of the ADT system. The extent of this zone will depend on the specific characteristics of the ADT system deployed, as well as the frequency and duration of the beam and any materials that it may interact with in its path.
- *Likely-exposed individuals*: Any individuals present in this zone may be exposed and will be highly dependent on the details of the scenario where the ADT system is used.
- *Dose sources in this zone*: All exposures in this zone will be to secondary radiation that has been produced, scattered or diffused into this zone but was generated from the interaction of the beam with nuclei in the air or particulates such as dust located in the beam path, or from the activation of environmental media.
- *Specific zone considerations*: Special care should be employed when deciding on ADT system deployment in order to minimize the dose potential in this zone. This

includes evaluating each type of potential deployment situation ahead of time as well as a case-by-case evaluation prior to each instance of deployment.

5.3 Radiation Environments of ADT Systems

The radiation hazards of photons produced by electron and proton accelerators need to be understood. While much of this information is well-known from applications in research and medicine, the specific conditions present during the use of an ADT system warrant special consideration. Quantitative dose assessment is essential to this process to ensure the proper design of bulk shielding and the development of appropriate engineering and administrative controls.

Beam hazards and the production of secondary particles, notably neutrons, need to be considered in any ADT system development and implementation. Additionally, any stray losses of beam may result in induced radioactivity through the activation of components or environmental media. These matters, well-known and well-quantified for proton and electron accelerators, have been discussed extensively elsewhere (Cossairt, 2009; NCRP, 2003c; Patterson and Thomas, 1973; Thomas and Stevenson, 1988).

ADT systems which utilize accelerators also include the use of additional hazardous substances or devices such as cryogenic systems, vacuum systems, laser aiming systems, chemical hazards, electrical hazards, RF generators, microwaves, etc. While the consideration of these potential hazards is beyond the scope of this Commentary, they must be considered in the development of the safety programs for the use of ADT systems.

5.3.1 *Beam and Prompt Radiation Fields*

The prompt radiation of particle accelerators exists only when they are in operation. Prompt radiation is present during machine operation and is due to the primary beam or beam interactions with machine components. Prompt radiations can represent extremely high dose rates, especially near the beam producing components. However, hazards due to prompt radiation disappear as soon as the beam is turned off.

Radiation from planned beam losses, for instance those occurring at any bending elements, collimators, targets and beam dumps, is easier to estimate than that from unplanned ones, due to incorrect beam steering. For the latter, it is necessary to make conservative assumptions[2] at the stage of shielding design and to monitor/terminate the beam losses by means of active interlocked devices. In general, the higher the energy of the particles accelerated the more complex the characteristics of the prompt radiation field can be. Since the hazard of prompt radiation can be very large in unshielded areas, in particular in the beam itself or within beam housings, interlocks or other area controls are necessary to prevent unauthorized or inadvertent access.

If shielding has been designed and installed correctly, prompt radiation will generally account only for a small fraction of the dose to operating personnel during routine ADT use. The prompt radiation field includes several different components: electrons, photons, neutrons and muons at higher energy accelerators.

[2]Assumptions that will tend to overestimate the magnitude of the impact.

Prompt radiation from accelerators is often pulsed, with a frequency that can range between millions of cycles per second (hertz) in a storage ring to as low as one pulse every minute in some rare types of one-pass accelerators. Most single-pass accelerators cycle at frequencies of many hertz. Special precautions must be taken to ensure the response time of detection instruments (which may be nonlinear and in the worst cases saturate above a certain peak dose rate level) is consistent with the design requirements.

For accelerator tuning, well-designed beam absorbers will be needed and, of necessity, will be custom designed. Likewise, sufficient bulk shielding will be needed to protect operators, maintenance personnel, and members of the public. The physical size of beam absorbers and bulk shielding for proton accelerators compared with their equivalent components used with electron accelerators will be larger, scaled according to the nuclear interaction length.

As with electromagnetic cascades, hadronic cascades resulting from proton interactions need to be understood fully to evaluate the radiological hazards. The dose per fluence factors for protons are well-known, and when multiplied by the proton fluence lead directly to the radiation dose from the direct proton beam used in an ADT system.

While somewhat similar in character to the prompt radiation hazards at electron accelerators, the prompt radiation hazards at proton accelerators external to radiation shielding is dimensionally scaled to the nuclear interaction length rather than to the radiation length. Also, the prompt radiation field at a medium to high energy proton accelerator will be much more dominated by the presence of neutrons, especially at forward angles relative to the incident proton beam. Likewise residual radiation fields at proton accelerators will be dimensionally scaled by the nuclear interaction rather than by the radiation length.

A general rule observed during operation of high energy proton accelerators in the latter part of the 1950s is that fast neutrons between 0.1 MeV and 10 MeV contributed more than 50 % of the dose equivalent of the radiation field outside such thick shields; photons and thermal neutrons contributed about 10 to 20 %, with the balance made up by neutrons >10 MeV (Thomas and Stevenson, 1988).

The charged particle environment outside high energy proton accelerator shields may include muons and protons as well. The physics of muon production and scattering is discussed by Stevenson (1976). Typically the presence of protons in the equilibrium radiation field outside the shielding of high energy accelerators would not contribute significantly to the dose equivalent (which is largely due to neutrons).

5.3.2 *Stray Radiation Fields*

Scatter fields can be assumed to include particles or photons that have undergone elastic and inelastic scattering in the air and, perhaps, in the water or soil. These scattering phenomena have more specifically been referred to as "skyshine" and "groundshine." Scatter intensities around ADT systems and at great distances from ADT systems (*e.g*. several blocks away, or across the river or port) will depend upon the effective source strength and emitted energy, the effective absorption length, and the distance from the beam apparatus. While it is expected that scatter components may be small fractions of the prompt beam radiation levels, it is important that they be considered, particularly for long air paths, for future ADT system development.

5.3.3 *Induced Radioactivity*

Residual radiation may be still present inside the accelerator housing after the beam is shut off at a much lower level compared to prompt radiation. This remnant radiation field results from the decay of radioactivity induced in the accelerator structure and its ancillary components by the interaction of the constituent particles and photons produced in the prompt radiation field. Such induced radioactivity may also be generated in lubricating materials or other environmental contaminates (especially if ADT systems are operated in dirty environments) and could represent removable radioactive contamination with associated hazards due to its inherent mobility. The precise characteristics of any such remnant field or removable contamination will depend on many factors such as the type and energy of the particles accelerated, the beam intensity and the particular materials irradiated by the primary and secondary radiations.

All particle accelerators whose energy exceeds 10 MeV will produce some induced radioactivity, and in the cases of light target nuclei (such as beryllium or lithium) radioactivity can be induced at energies well below 10 MeV (Thomas and Stevenson, 1988). Materials can be activated by the high energy electrons, protons, and especially neutrons of all energies which are produced when the beam hits an accelerator component. Two common production mechanisms include photodisintegration and neutron capture, represented below:

$$\text{photodisintegration (if photoneutron): } X + {}^{A}_{Z}T = n + {}^{A-1}_{Z}D\,, \tag{5.1}$$

and

$$\text{neutron capture: } n + {}^{A}_{Z}T = {}^{A+1}_{Z}D\,, \tag{5.2}$$

where:

T target nuclide

D target nuclide daughter

X x-ray photon with an energy sufficiently high to induce photodisintegration

n neutron produced

Note that a photodisintegration can also be a photo-proton event (or a photoneutron/proton event) if the photon energy is sufficiently high.

At high energy accelerators, all nuclides with atomic and mass number lower than those of the irradiated material can be produced. Of those nuclides, some are stable, while others are radioactive with a wide range of half-lives. Table 5.1 lists radionuclides commonly identified in solid materials irradiated around high energy accelerators. Table 5.2 lists radionuclides commonly associated with the operation of bremsstrahlung systems (such as medical electron accelerators).

Most of the radionuclides listed in Tables 5.1 and 5.2 are produced by the simple nuclear reactions discussed above, but some result from spallation, fragmentation or more complicated

Table 5.1—*Radionuclides commonly identified in solid materials irradiated around accelerators (NCRP 2003c; Patterson and Thomas, 1973).*

Irradiated Material	Radionuclides
Water, plastics, oils	^{7}Be, ^{11}C
Aluminum	As above, plus ^{22}Na, ^{24}Na, ^{32}P, ^{42}K, ^{45}Ca
Iron, steel	As above, plus ^{44}Sc, ^{44m}Sc, ^{46}Sc, ^{47}Sc, ^{48}Sc, ^{48}V, ^{52}Cr, ^{52}Mn, ^{52m}Mn, ^{54}Mn, ^{56}Mn, ^{57}Co, ^{58}Co, ^{60}Co, ^{57}Ni, ^{55}Fe, ^{59}Fe
Copper	As above, plus ^{65}Ni, ^{61}Cu, ^{64}Cu, ^{63}Zn, ^{65}Zn

Table 5.2—*Radionuclides commonly associated with the operation and decommissioning of typical medical linear accelerator machines (Wang et al., 2005; Williamson et al., 2010).*

Operational Mode	Radionuclides
Operating LINAC	^{24}Na, ^{28}Al, ^{54}Mn, ^{56}Mn, ^{57}Ni, ^{53}Fe, ^{59}Fe, ^{58}Co, ^{62}Cu, ^{64}Cu, ^{82}Br, ^{122}Sb, and ^{187}W
Decommissioned LINAC	
• lead shielding	^{124}Sb
• flattening filter	^{57}Co, ^{58}Co, ^{60}Co, ^{54}Mn
• target	^{57}Co, ^{58}Co, ^{60}Co, ^{54}Mn, ^{97}Zr, ^{125}Sb, ^{187}W
• steel housing	^{58}Co, ^{60}Co, ^{97}Zr

capture reactions. Compilations of measured cross-sections and codes to predict cross-sections from intra-nuclear cascade calculations are available (Barbier, 1969; Bruninx, 1964).

The decay of the radioactivity associated with accelerator structures is a complex function of time. Sullivan and Overton (1965) have derived an approximate analytical expression that gives the dose rate, $\dot{D}$, from induced radioactivity at time *t* after the irradiation ceases:

$$\dot{D}(t) = B\phi \ln\left(\frac{T+t}{t}\right), \tag{5.3}$$

where:

T	=	irradiation time
ϕ	=	fluence rate of irradiating particles
B	=	parameter that depends upon the target, geometrical and irradiation conditions

The activity of radionuclides with short half-lives is quickly saturated when the beam is on and quickly disappears by decay when the beam is off, while very long-lived radionuclides build up and decay very slowly. As a result, the most abundant radionuclides are those with a half-life of the order of the irradiation time. However, the long-lived radionuclides produced can represent a concern during ADT system dismantling and decommissioning activities in the future (Table 5.2).

Most residual radionuclides emit beta and gamma radiation, which is easily measured with common radiation detectors. In general, gamma radiation is the most important issue and is the source of the largest fraction of total individual doses at most accelerators. Beta radiation is only important when handling very radioactive thin objects (for instance small targets): in those cases it can be a concern for the eye and extremity doses. Contrary to other types of radiological facilities, induced activity at high energy accelerators tends to be distributed in volume rather than concentrated at the surface.

For a given location and fixed geometrical and irradiation conditions, the activation dose rate, R_c , at decay time t_d, following a continuous irradiation of time t_r, due to a particular radionuclide of decay constant λ will be given by the following (assuming no prior activation):

$$R_c = R_s \left(1 - e^{-\lambda t_r}\right) e^{-\lambda t_d} , \tag{5.4}$$

where R_s is the saturation dose rate which represents the maximum dose rate that would be achieved immediately following a prolonged continuous irradiation. If during the decay period, exposure to the source of activation begins at time t_{d1} and ends at time t_{d2} after the irradiation, then the dose received by induced activity, D_c, may be written as $D_c = KR_c$, where:

$$K = \frac{e^{-\lambda t_{d1}} - e^{-\lambda t_{d2}}}{\lambda e^{-\lambda t_d}} , \tag{5.5}$$

5.3.4 *Fission*

A specialized potential use of photons in ADT systems is to optimize them to exploit photon-induced fission (photofissions). In photofission, the photon radiation would be optimized to promote the nuclear fission of SNM present in a suspect container or vehicle. The unique, prominent signature of the radiation produced in the fission process would drive the design of the associated detection system.

Proton beams can induce fission both directly via a proton-fission process when incident on SNM and indirectly through the production of neutrons subsequently available for the induction by either thermal neutron capture or fast neutron processes by SNM. A proton beam incident on material could also induce fission due to the interactions of neutrons produced secondarily or in a hadronic cascade. While the radiations produced are secondary to that of the direct hazard "in the beam," they need to be quantified to evaluate fully the radiological hazard. If thermal neutron capture is involved, then an assessment of the impact of these exothermic reactions needs to be considered to complete the necessary hazard assessment.

While accelerator-produced neutrons would be secondary particles of almost certainly lower fluence rate than that of the primary protons, the neutron hazard should be quantified as well as the emissions of any fission process that might result. The neutron hazard, dependent upon both the choice of technology and the configurations of the actual ADT systems could involve both fast and moderated (thermalized) neutrons. If thermal neutrons are involved, the possibility of exothermic thermal neutron capture reactions may be a factor on the necessary hazard assessment.

5.3.5 *Radionuclides Produced in the Environment*

It is essential to consider the spectrum of particles leaving the ADT system and the scattering and transport of these particles in the air/ground/water/building complex to the point where they can produce radionuclides in the environment. However, environmentally produced radioactivity is expected to be much less than the radioactivity induced in the ADT system components due to the short interrogation time. For example, even in strong focusing accelerators (*e.g*., Brookhaven AGS or CPS) operating at gigaelectron volt levels, 93 % of the radioactivity produced was found in the accelerator components, bending magnets and the concrete room, while 5 % of the radioactivity was produced in the earth, and 1 % was produced in groundwater (Thomas and Stevenson, 1988).

The principal source of radioactivity in air is the interaction of primary and secondary particles directly with constituent target nuclei of the air. A secondary source of airborne activity is dust. A third source might result from the emission of gaseous radioactivity from liquids irradiated by the ADT system. Due to the most abundant stable isotopes in the atmosphere, the radionuclides of significance for environmental contamination are ^{11}C, ^{13}N, and ^{15}O and perhaps ^{3}H and ^{7}Be.

While the radionuclides induced in the ADT system components and shielding are relatively immobile, the radionuclides produced in the earth or groundwater (or sea) may be able to move. It is also possible that activity induced in the earth may be leached into the groundwater system and should also be considered, although it is expected to be rather small. In any case, the evaluation of soil induced radioactivity should include consideration of the possible radionuclides that could be produced based on the chemical composition of the rock and water impurities (difficult for present ADT system suggested use), an estimate of the yield of these radionuclides from known production cross-sections, radioactive half-life, particle flux densities and energy spectra. Radionuclides produced in earth may include ^{7}Be, ^{45}Ca, ^{43}K, ^{32}P, ^{47}Sc, ^{55}Fe,

^{59}Fe, ^{60}Co, ^{54}Mn, ^{22}Na, or others depending upon the factors discussed above. A good study of the leaching of accelerator-produced radionuclides into soil is that of Borak *et al*. (1972).

5.3.6 *Muon Considerations*

Note that all proton accelerators in the energy range under consideration (500 MeV to 10 GeV) are capable of producing muons and need to address the muon hazard either with bulk shielding or magnetic dispersal. Muons in this energy domain do not generally experience nuclear interactions so that their attenuation must rely upon energy losses through ionization processes. Ionization ranges of muons in solid materials are quite large. For example, the range of 400 MeV muons in earth is ~11 m and in iron is ~2 m (Cossairt, 2009; Fasso *et al*., 1990). Fortunately, given the fact that muons primarily interact electromagnetically, the dosimetry is simple and has been well-described elsewhere (Fasso *et al*., 1990; Stevenson, 1983).

Because muon interactions are dominated by electromagnetic interactions, they behave in matter as would heavy electrons and have, to a good approximation, a radiation weighting factor of unity. Stevenson (1983) has provided values of fluence-to-dose equivalent conversion factors over a wide domain of muon energies. It is straightforward to calculate the dose equivalent by multiplying this factor by the fluence, especially given the very weak energy dependence that is also discussed by Stevenson (1983).

5.4 Hypothetical Dose Ranges

To compare with the dose limit of 5 mSv per interrogation event recommended by NCRP Commentary No. 21 (NCRP, 2011), the effective dose to an individual exposed to the beam as well as the dose from the scattered beam and/or any secondary radiation coming from the scanned object needs to be estimated for the system with specific beam-object-detector parameters.

This section gives examples of such dose calculations for a bremsstrahlung beam from an electron accelerator (15 MeV and 20 MeV maximum) and proton beam (1 GeV and 10 GeV) of a proton accelerator. These analytic calculations are meant to illustrate the parameters and conditions that are important to the dose estimations. They do not represent actual system parameter values. More accurate calculations using a Monte-Carlo code with actual system parameter values and conditions are recommended in order to compare the estimated dose with the NCRP recommended dose limit of 5 mSv per interrogation event.

Note that the specific system parameters and operating conditions for radiation beam, object being scanned, and the detector system have not been specified. To meet SNM interrogation performance requirements and goals, the system parameters and operating conditions are expected to vary by a wide range. Some of those parameters and conditions will affect the dose estimations. Therefore, the evaluation of effective dose to an exposed individual needs to be part of the system design considerations and process. Radiological safety considerations should also be part of the optimization of the system design and performance.

5.4.1 *Examples of Effective Dose Calculations*

5.4.1.1 *Assumptions.* The following assumptions are used in the dose calculations:

- The radiation source (or interrogation beam) is either a bremsstrahlung beam from an electron beam (maximum 15 MeV or 20 MeV at the same average current) hitting an optimized target or a proton beam (1 GeV or 10 GeV at the same average current) from a proton accelerator.
- The source-to-object distance (STO) = 100 m, and an object-to-detector distance, OTD = 50 m (these are the minimum distance requirements).
- The object of interest is SNM material [weapons grade uranium (WGU) or weapons grade plutonium (WGPu)]. The beam size at the object location should be large enough to cover the potential SNM material surface area:
  - The bremsstrahlung beam size at the object location is limited by the accelerator system collimator system. The beam size A_x at the object location is assumed to be 100 × 100 cm = 10,000 cm^2 [based on nominal data provided by DTRA for the laboratory type bremsstrahlung system]. The angle of half bremsstrahlung intensity for 15 MeV or 20 MeV beams, estimated from Equation 3.9 of NCRP (2003c), is much larger than the collimator angle, which is less than one degree. Therefore, the bremsstrahlung beam intensity within the beam area is nearly constant.
  - The proton beam size is assumed to be 1 cm^2 at 1 m and 1 m^2 at 100 m (the same as the bremsstrahlung beam technology).
- When calculating detector signals for signature radiation, SNM surface area (145 cm^2 for 25 kg of WGU) is used. When calculating the object-scattered doses to nearby

personnel, a high-*Z* object such as lead hit by the whole beam size (*i.e.*, 10,000 cm^2 at object location) is used.

- A dwell time (*t*) is needed for the beam to irradiate SNM object to induce sufficient signals for the detectors. The dwell time depends on the beam intensity, the object-to-detector distance, the signature radiation, the detector system, and the signal-to-noise ratio.
    - A dwell time of 120 s is assumed for the 20 MeV bremsstrahlung beam, based on the nominal data of the laboratory-type bremsstrahlung system (NOMI, 2010). A dwell time of 240 s is then needed for the 15 MeV bremsstrahlung beam at the same beam current.
    - A dwell time of 30 s is assumed for the 1 GeV proton beam.

5.4.1.2 *Process of Individual Dose Calculations.* The dose calculations consist of the following four steps:

1. determination of radiation source term (*i.e.*, in-beam, zero degree dose rate at 1 m);
2. calculation of in-beam dose rate at the object location by considering the STO distance (inverse-square law) and attenuation of air and potential object shielding;
3. calculation of dose rate for any secondary radiation scattered or generated from the scanned object by considering object-to-personnel distance and the potential object shielding; and
4. calculation of doses to an individual for both the in-beam dose and secondary radiation dose by considering the needed dwell time on potential SNM material and total scanning time for the subject of interrogation (*e.g.*, the ship), respectively.

For the purpose of assessing potential radiation doses, NCRP assumes nominal values of system parameters. These values and calculation results are summarized in Table 5.3 (bremsstrahlung beam) and Table 5.4 (proton beam). A comparison of the radiation doses at the object for bremsstrahlung and proton beams is given in Table 5.5.

Step 1: Radiation source term:

The in-beam, zero degree dose rate at 1 m can be estimated from the accelerator beam parameters of the beam energy and average current.

Bremsstrahlung beam:

For the zero degree, thick-target bremsstrahlung dose from a high-*Z* target hit by an electron beam, Figure 3.5 or Equation 3.6 of NCRP (2003c) [or Figure E.1 of NCRP (1977) can be used (NCRP, 1977; 2003c)]. The normalized source terms are 0.017 Gy s^{-1} μA^{-1} and 0.034 Gy s^{-1} μA^{-1} for 15 MeV and 20 MeV beams, respectively. With the electron beam parameters (average current 8.4 μA) shown in Table 5.3, the bremsstrahlung dose rates at zero degree and 1 m from the electron beam target are 0.14 Sv s^{-1} and 0.28 Sv s^{-1} for 15 MeV and 20 MeV beams, respectively.

The calculated 20 MeV dose rate is within a factor of two of the nominal data for the laboratory-type bremsstrahlung beam system (0.42 Sv s^{-1} for the 20 MeV beam) (NOMI, 2010).

Table 5.3—*Dose calculations for a bremsstrahlung beam from an electron accelerator at 15 or 20 MeV.*

In-Beam, Zero Degree Bremsstrahlung Photon Dose	Case 1 Value	Case 2 Value
Electron kinetic energy (MeV) [a]	15	20
Peak current (mA)	35	35
Pulse frequency (Hz)	60	60
Pulse length (μs)	4	4
Average current, I (μA)	8.4	8.4
Average beam power (W)	126	168
Normalized photon dose rate at 1 m, D_n (Gy s^{-1} μA^{-1}) [b]	0.017	0.034
Photon dose rate at 1 m, $D_o = D_n I$, (Sv s^{-1})	0.14	0.28
Source-to-object distance, d_1 (m) [c]	*100*	*100*
Attenuation in air d_1, T_{air} [d]	0.8	0.8
Attenuation in object shielding, T_{tar} [e]	*1.0*	*1.0*
Photon dose rate at object, $D_t = 1{,}000\ D_o\ T_{air}\ \mathrm{T}_{tar} / d_1^2$, (mSv s^{-1})	0.011	0.022
Needed dwell time on object, t (s) [f]	*240*	*120*
Photon dose at object, $D = D_t\ t$ (mSv) [g]	**2.7**	**2.7**
Photon fluence rate at object, $\phi_x = D_t / h_x$ (cm^{-2} s^{-1}) [h]	5.5×10^5	1.1×10^6
Photon fluence at object, $F_x = \phi_x t$, (cm^{-2})	1.3×10^8	1.3×10^8
Object cross section to generate signature radiation, σ_s (barn) [i]	0.3	0.3
Object-to-detector distance, d_2 (m) [c]	*50*	*50*
Detector signal, $S = \phi_x A_t\ \sigma_s A_d\ \eta / (4\pi\ d_2^2)$ [j]	unknown	unknown
Signal-to-noise ratio [k]	unknown	unknown
Angle of half bremsstrahlung intensity (degrees) [l]	6.7	5

Object-Scattered Doses	Value	Value
Photon scattering ratio, R_x [m]	0.01	0.01
Scattered dose rate at 1 m from object, $D_s = D_t R_x$ (mSv s^{-1})	1.1×10^{-4}	2.2×10^{-4}
Photoneutron dose rate at 1 m from object, D_{xn} (mSv s^{-1}) [n]	4.4×10^{-6}	1.8×10^{-5}
Photoneutron fluence rate at detector location, d_2 , ϕ_{xn} (cm^{-2} s^{-1}) [o]	5.9×10^{-3}	2.4×10^{-2}
Photofission neutron fluence rate from SNM at d_2 , ϕ_{fn} (cm^{-2} s^{-1}) [p]	1.1×10^{-3}	4.4×10^{-3}

[a]Maximum kinetic energy of the electron accelerator beam.
[b]The zero degree, thick-target bremsstrahlung dose from a high-*Z* target from NCRP (2003c) Figure 3.5 (or NCRP, 1977, Figure E.1).
[c]The source-to-object distance (d_1) and the object-to-detector distance (d_2) are assumed to be 100 and 50 m, respectively (the minimum distance requirements).
[d]Calculated with an air length of d_1, an air density of 0.001205 g cm^{-3}, and an attenuation coefficient of 0.02 cm^{-2} g^{-1}.
[e]No attenuation of photons in object shielding assumed.
[f]A dwell time of 120 s for 20 MeV beam based on the bremsstrahlung system nominal data (240 s for 15 MeV beam at the same beam current).
[g]The dose to object is to be compared with the NCRP recommended dose limit of 5 mSv.
[h]Calculated with a photon fluence-to-effective dose conversion coefficient $h_x = 2 \times 10^{-11}$ Sv cm^2.
[i]The object cross section to generate the signature radiation for the detector (*e.g.*, 0.3 barns for photofission).
[j]Detector signal (S) depends on the beam fluence rate on object (ϕ_x), the SNM object surface area (*e.g.*, A_t = 145 cm^2 for 25 kg of WGU), object cross section for signature radiation (σ_s), the object-to-detector distance (d_2), detector surface area (A_d), and the detector efficiency for signature radiation (η). This value is left as unknown as it depends on the detector system, which is unknown at this time.
[k]The signal-to-noise ratio depends on the signature radiation, detector system, and ambient radiation environment (also footnote p).
[l]The angle of half bremsstrahlung intensity (degrees) from NCRP (2003c) Equation 3.9.
[m]From NCRP (2003c), Figure 4.12 (or NCRP, 1977, Figure E.15)
[n]The effective dose (or fluence) rate for photoneutrons from a high-*Z* material (lead assumed) hit by photon beam is calculated conservatively with the following parameters:

N_A	=	6.02×10^{23} atom cm^{-3}
ρ	=	density of high-*Z* object = 11.34 g cm^{-3}
M	=	atomic mass of the material = 207 g mole^{-1}
σ	=	photoneutron cross section = 0.1 barn atom^{-1} for 15 to 20 MeV beam
ϕ_x	=	photon fluence rate and a fraction of 0.1 (0.2 for 20 MeV) for photons with a 1/E spectrum above the photoneutron threshold of 10 MeV
A_x	=	photon beam size at STD = 100 cm × 100 cm = 10,000 cm^2 (prototype system data)
h_n	=	giant-resonant photoneutron fluence-to-effective dose conversion coefficient = 3×10^{-10} Sv cm^2

[o]Isotropic emission of photoneutrons is assumed (d_2 = 50 m from object).
[p]The photofission neutron fluence rate from a SNM object at detector location (d_2 = 50 m from object), calculated similar to footnote n, except that a photofission cross section of 0.3 barn, three neutrons per fission, and A_t = 145 cm^2 for SNM were used. The delayed photofission neutron fluence rate at detector is a factor of 100 lower than the prompt neutron. These can be compared with the cosmic neutron fluence rate of 8×10^{-3} cm^{-2} s^{-1} at sea level.

Table 5.4—*Dose calculations for proton beam (1 and 10 GeV) of a proton accelerator*.

In-Beam, Zero Degree Dose	Case 1 Value	Case 2 Value
Proton kinetic energy (GeV)	1	10
Peak current (μA)	0.5	0.5
Pulse frequency (Hz)	60	60
Pulse length (μs)	4	4
Average current, *I* (nA)	0.12	0.12
Proton beam power (W)	0.12	1.2
Proton beam intensity, *I* (p s^{-1})	7.5×10^8	7.5×10^8
Proton beam size at 1 m (cm^2) [a]	*1*	*1*
Proton fluence rate at 1 m (cm^{-2} s^{-1})	7.5×10^8	7.5×10^8
Proton-to-effective-dose conversion factor (Sv cm^2)	3×10^{-9}	4×10^{-9}
Proton effective dose rate at 1 m, D_o (Sv s^{-1}) [b]	2.25	3.0
Source-to-object distance, d_1 (m) [c]	*100*	*100*
Attenuation in air d_1, T_{air} [d]	0.82	0.82
Proton range in air (m)	2,300	40,000
Attenuation in object shielding, T_{tar} [e]	*0.84*	*0.84*
Proton dose rate at object, $D_t = 1{,}000\ D_o\ T_{air}\ T_{tar} / d_1^2$ (mSv s^{-1}) [f]	0.16	0.21
Needed dwell time on object, *t* (s) [g]	*30*	*15*
Proton dose at object, $D = D_t\ t$ (mSv) [h]	**4.7**	**3.1**
Proton fluence rate at object, $\phi_p = D_t / h_p$ (cm^{-2} s^{-1})	5.2×10^4	5.2×10^4
Proton fluence at object, $F_p = \phi_p\ t$, (cm^{-2})	1.6×10^6	7.8×10^5
Proton beam size at object (cm^2) [a]	*10,000*	*10,000*
Object cross section to generate signature radiation, σ_s (barn) [i]	*unknown*	*unknown*
Object-to-detector distance, d_2 (m) [c]	*50*	

Detector signal, $S = \phi_p A_t \sigma_s A_d \eta / (4\pi d_2^2)$ [j]	unknown	unknown
Signal-to-noise ratio [k]	unknown	unknown
Object-Scattered Doses	**Value**	**Value**
Neutron per proton on a high-Z object [l]	20	40
Proton-neutron dose rate at 1 m from object, D_n (mSv s^{-1}) [m]	3.3×10^{-2}	6.6×10^{-2}
Proton-neutron fluence rate at d_2, ϕ_n (cm^{-2} s^{-1}) [n]	33	66

[a]Proton beam size is assumed to be 1 cm^2 at 1 m and 1 m^2 at 100 m (the same as the bremsstrahlung beam technology).
[b]Calculated with a proton fluence-to-effective dose conversion coefficient $h_p = 3 \times 10^{-9}$ Sv cm^2 and 4×10^{-9} Sv cm^2, for 1 GeV and 10 GeV proton beams, respectively.
[c]The source-to-object distance STO (d_1) and the object-to-detector distance OTD (d_2) are assumed to be 100 and 50 m, respectively (the minimum distance requirements).
[d]Calculated with an air length of d_1, an air density of 0.001205 g cm^{-3}, and a removal mean free path of 62 g cm^{-2}.
[e]Calculated with lead thickness of 20 g cm^{-2} and removal mean free path of 116 g cm^{-2}.
[f]Proton dose rate at object.
[g]A dwell time of 30 s is assumed for 1 GeV beam (15 s for 10 GeV beam as the neutron detector rate is twice higher).
[h]The dose to object is to be compared with the NCRP recommended dose limit of 5 mSv.
[i]The object cross section to generate the signature radiation for the detector. This parameter depends strongly on the beam type and detector measurement principle. This value is left as unknown as it depends on the detector system which is unknown at this time.
[j]Detector signal (S) depends on the beam fluence rate on object (ϕ_x), the SNM object surface area (A_t = 145 cm^2 for 25 kg of WGU), object cross section for signature radiation (σ_s), the object-to-detector distance (d_2), detector surface area (A_d), and the detector efficiency for signature radiation (η). See footnote i.
[k]The signal-to-noise ratio depends on the signature radiation, detector system, and ambient radiation environment. See footnote i.
[l]Neutron yield per proton hitting a thick, high-Z object.
[m]The effective dose rate for neutrons from a high-Z material hit by high-energy proton beam is calculated with the following parameters and assumptions:

ϕ_p = proton fluence rate at object
A_t = beam size of 10,000 cm^2

Neutron yield of 20 and 40 for 1 GeV and 10 GeV protons, respectively
Isotopic neutron emission
No neutron attenuation of object shielding
[n]Neutron fluence-to-effective dose conversion coefficient = 4×10^{-10} Sv cm^2

Table 5.5—*Summary of calculated radiation doses at object from bremsstrahlung beams and proton beams considered for ADT systems.*

Beam Description	Dose at Object (mSv)
Bremsstrahlung beam from 15 MeV electron accelerator	2.7
Bremsstrahlung beam from 20 MeV electron accelerator	2.7
Proton beam from 1 GeV proton accelerator	4.7
Proton beam from 10 GeV proton accelerator	3.1

Proton beam:

With the proton beam parameters (average current 0.12 nA and a beam size of 1 cm^2 at 1 m) shown in Table 5.4, the proton dose rates at zero degree and 1 m are 2.25 Sv s^{-1} and 3.0 Sv s^{-1} for 1 GeV and 10 GeV beams, respectively. These were calculated with proton fluence-to-effective dose conversion coefficients of 3×10^{-9} Sv cm^2 and 4×10^{-9} Sv cm^2 for 1 GeV and 10 GeV proton beams, respectively (Pelliccioni, 2000).

Step 2: In-beam dose rate at the object location

Bremsstrahlung beam:

Only air attenuation was considered for the dose calculations to an individual. The in-beam dose rate at the object location can be calculated using an air length of STO = 100 m, an air density of 0.001205 g cm^{-3}, and an attenuation coefficient of 0.02 cm^2 g^{-1}.

The bremsstrahlung dose rates at the object location are 0.011 mSv s^{-1} and 0.022 mSv s^{-1} for 15 MeV and 20 MeV beams, respectively.

The photon fluence rate at the object location can be calculated to be 5.5×10^5 cm^{-2} s^{-1} and 1.1×10^6 cm^{-2} s^{-1} for 15 MeV and 20 MeV beams, respectively, using a photon fluence-to-effective dose conversion coefficient h_x of 2×10^{-11} Sv cm^2 (Pelliccioni, 2000).

Proton beam:

Air attenuation and object shielding were considered for the dose calculations to an individual.

The attenuation can be calculated using an air length of STO = 100 m and an air density of 0.001205 g cm^{-3}, as well as a lead shielding of 20 g cm^{-2} thick. For gigaelectron volt proton beams, the removal mean free path is 62 g cm^{-2} for air and 116 g cm^{-2} for lead (Table 3.3 of NCRP, 2003c). The calculated attenuation factor for air and object shielding were 0.82 and 0.84, respectively.

The proton dose rates at the object location are then 0.16 mSv s^{-1} and 0.21 mSv s^{-1} for 1 GeV and 10 GeV beams, respectively.

Step 3: Dose rates from secondary radiations:

Bremsstrahlung beam:

When a 15 MeV or 20 MeV bremsstrahlung beam scans an object, photons can be scattered from the object and giant-resonant photoneutrons (peaked at 1 to 2 MeV) can also be produced from the scanned object (or photofission from a SNM object).

The scattered photon dose rate at 1 m from the object can be estimated to be 1.1×10^{-4} mSv s^{-1} and 2.2×10^{-4} mSv s^{-1} for 15 MeV and 20 MeV beams, respectively, using a reflection coefficient of 0.01 from Figure 4.12 of NCRP (2003c) (or Figure E.15 of NCRP, 1977).

The photoneutron dose rate at 1 m from a high-*Z* material (lead assumed) hit by a bremsstrahlung beam can be estimated conservatively to be 4.4×10^{-6} and 1.8×10^{-5} mSv s^{-1} for 15 and 20 MeV beams, respectively, with the following parameters:

N_A = 6.02×10^{23} atom cm^{-3}

M = atomic mass of the high-Z object = 207 g mole^{-1}

ρ = density of the high-Z object = 11.34 g cm^{-3}

σ = photoneutron cross section = 0.1 barn atom^{-1}

A_x = bremsstrahlung beam size at object location (STO = 100 m) is 100 cm × 100 cm = 10,000 cm^2

ϕ_x = photon fluence rate at object location (STO = 100 m) with a 1/E spectrum (5.5×10^5 cm^{-2} s^{-1}) and the fractions for photons above the photoneutron threshold of 10 MeV are 0.1 and 0.2 for 15 MeV and 20 MeV beams, respectively

h_n = fluence-to-effective dose conversion coefficient for giant-resonant photoneutrons = 3×10^{-10} Sv cm^2 (Pelliccioni, 2000)

Proton beam:

When a GeV proton beam scans an object, the main secondary radiation is from neutrons (with a peak at 1 MeV to 2 MeV and neutrons up a few hundred MeV). There are other secondary particles such as protons, muons and photons, but their magnitudes are lower than neutrons and can be ignored for the dose estimations).

The neutron dose rate at 1 m from a lead object hit by a proton beam can be estimated to be 3.3×10^{-2} mSv s^{-1} and 6.6×10^{-2} mSv s^{-1} for 1 GeV and 10 GeV beams, respectively, with the following parameters:

neutron yields per proton = 20 for 1 GeV proton and 40 for 10 GeV proton (Figure 3.21 of NCRP, 2003c)

A_x = proton beam size at object location (STO = 100 m) is 100 cm × 100 cm = 10,000 cm^2

h_n = fluence-to-effective dose conversion coefficient for proton-induced neutrons = 4×10^{-10} Sv cm^2

Step 4: Doses to an individual:

Note that the dose calculations for an exposed individual consider either no shielding or minimal shielding of the SNM object (Step 2). The SNM object may have thicker shielding to attenuate the interrogation beam such that a longer dwell time is needed and the dose to the exposed individual will be higher.

In addition, individuals at far distances (not irradiated by the direct beam) may be exposed to secondary radiation during the entire scanning period (which may be much longer than the needed dwell time for a SNM object). The prolonged exposure of more people to low levels of radiation may also need to be considered.

Bremsstrahlung beam:

The scattered photon dose rate and the photoneutron dose rate at 1 m from the scanned object are only 1 % and 0.1 % of the in-beam bremsstrahlung dose rate, respectively. Therefore, the in-beam dose rate can be used to estimate the dose to an exposed individual.

Assuming a dwell time of 240 s for 15 MeV beam (or 120 s for 20 MeV beam) on a SNM object is needed, the estimated effective dose to an exposed individual is 2.7 mSv. The dose is approximately a factor of two smaller than the limit of 5 mSv recommended by NCRP Commentary No. 21 (NCRP, 2011).

Proton beam:

The secondary neutron dose rate at 1 m from the scanned object is 20 % to 30 % of the in-beam proton dose rate. Therefore, the in-beam dose rate can be used to estimate the dose to an exposed individual.

Assuming a dwell time of 30 s for 1 GeV beam (15 s for 10 GeV beam) on a SNM object is needed, the estimated effective dose to an exposed individual is 4.7 mSv for 1 GeV beam (3.1 mSv for 10 GeV beam). The doses estimated are slightly lower than the limit of 5 mSv recommended by Commentary No. 21 (NCRP, 2011). Therefore, with a reasonable set of assumptions and given inherent uncertainties, the estimated doses approach the 5 mSv limit recommended by Commentary No. 21. Designing and operating an ADT system in such a way that it meets the limit of 5 mSv with a margin of safety will likely be challenging.

5.4.2 *Detector Considerations*

The detector system should be optimized to detect the signature radiation (gammas, neutrons or other types of radiation, depending on the interrogation beam and detector system) from the SNM object with acceptable dwell time, signal-to-noise ratio, and detection time. The detector information is crucial to the determination of beam system parameters.

The detector's signal-to-noise ratio depends on the signature radiation, detector system, and ambient radiation environment. If the detector relies on the neutron detection, the following analysis can be used to evaluate the detector's signal-to-noise ratio.

Bremsstrahlung beam

- Based on the analysis in Step 3, the photoneutron fluence rates from a high-Z object at the detector location (OTD = 50 m) are 5.9×10^{-3} and 2.4×10^{-2} cm^{-2} s^{-1} for 15 and 20 MeV bremsstrahlung beams, respectively.
- The photofission neutron fluence rate from a SNM object at the detector location can also be calculated in a similar way. The photofission neutron fluence rates are estimated to be 1.1×10^{-3} cm^{-2} s^{-1} and 4.4×10^{-3} cm^{-2} s^{-1} for 15 MeV and 20 MeV bremsstrahlung beams, respectively, using a photofission cross section of 0.3 barn, three neutrons per fission, and a SNM object area of 145 cm^2 (while 10,000 cm^2 was used for photoneutrons from a high-Z object).
- Due to the cross section difference, the delayed photofission neutron fluence rate at the detector is a factor of ~100 lower than the prompt fission neutrons.
- The photoneutron fluence rate and photofission neutron fluence rate for a 20 MeV bremsstrahlung beam are higher than or comparable to the cosmic neutron fluence rate of 8×10^{-3} cm^{-2} s^{-1} at sea level (for 15 MeV beam, the photoneutron fluence rate and photofission neutron fluence are lower than the cosmic neutrons). Therefore, a bremsstrahlung beam with a higher energy and/or intensity and/or a neutron detection procedure utilizing time-tagged techniques seem to be necessary to increase the neutron signal-to-noise ratio.

Proton beam

The neutron fluence rate at the detector location (50 m from a lead object hit by a proton beam) can be estimated to be 33 cm^{-2} s^{-1} and 66 cm^{-2} s^{-1} for 1 GeV and 10 GeV beams, respectively. Though these neutrons are much higher than the cosmic neutron fluence rate of 8×10^{-3} cm^{-2} s^{-1} at sea level, these neutrons cannot be differentiated from neutrons resulting from protons hitting a SNM object. Therefore, other signature radiations from a SNM object that can be differentiated from the neutrons coming from ordinary objects seem to be necessary.

5.4.3 *Other Considerations*

The dwell time depends strongly on the types of signature radiation, the detector system, the object-to-detector distance, and the signal-to-noise ratio. The detector system should be optimized to reduce the dwell time and total scanning time so that the unwanted doses to personnel can be kept ALARA.

5.4.4 *Engineered Safety System Considerations*

Based on the above dose analysis, the following engineered safety systems are recommended to control the doses to a bystander and nearby personnel:

- accelerator system parameters (*e.g*., beam current, dwell time, and scanning speed and time) should be monitored and controlled;
- variable passive and/or active collimator systems should be used to limit the beam sizes at far distances; and

- radiation environment (*e.g.*, in-beam dose rates at 1 m and the object location, out-of-beam dose rates) should be monitored and controlled.

6. Radiation Protection Controls on ADT Systems

The radiation characteristics of particle accelerators, including those technologies that might be of use in ADT systems, are well known. Their associated radiological hazards to personnel and the environment as well as their mitigation have been extensively discussed in a number of references (Cossairt, 2009; Cossairt *et al*., 2008; Fasso *et al*., 1990; ICRU, 1978; NCRP, 1989; 2003c; Patterson and Thomas, 1973; Sullivan, 1992; Swanson, 1979; Swanson and Thomas, 1990; Thomas and Stevenson, 1988). NCRP has provided extensive general guidance on radiation protection for particle accelerator facilities (NCRP, 2003c) and for radiation protection programs in general (NCRP, 1998). In addition, NCRP has provided specific guidance on radiation protection and limits in Commentary No. 21 (NCRP, 2011), including output determinations, interlock systems, emergency response, determination of doses to individuals and notification, as well as general safety design features such as shielding, active radiation control systems, and access controls. This section focuses on additional design and operational controls that must be considered in assessing the safety of proposed ADT systems. Specific radiation protection controls should be based on the specific ADT system and should be determined following a specific integrated safety assessment approach, such as given by the U.S. Nuclear Regulatory Commission (NRC, 2001).

Radiation protection controls provide means to ensure that dose limits are reliably met. The type and amount of control used for any specific practice should be appropriate for the potential radiation dose from the practice. There are two types of controls, engineered and administrative. Engineered controls are the first layer of protection. As the possible hazard increases from a failure of controls the importance of reliable engineered controls also increases.

Administrative controls are subject to human error, failure due to complacency or budget cuts, and drift due to personnel turnover or other institutional changes.

Dose limitation is the responsibility of both manufacturers and users. Generally the manufacturer sets performance specifications to meet the system requirements and provides information characterizing the system elements relevant to radiation safety. Only the user can implement a practice that is optimized to ensure that doses are minimized. Procuring equipment that has the appropriate engineered controls is not sufficient to ensure safety. Proper implementation of administrative controls is critical.

Manufacturers, distributors and users of security screening systems should be aware of the applicable requirements in the U.S. Code of Federal Regulations (CFR). At a minimum the relevant regulations include:

- Title 21 CFR Parts 1000 through 1005 (FDA), apply to manufacturers of electronic products;
- Title 10 CFR Parts 20 and 30 through 33 (NRC), regarding radioactive materials; and
- Title 29 CFR Part 1910.1096 (OSHA), regarding occupational safety.

In addition during manufacturing, assembly, testing and use on property that is not federally owned or controlled, the installation, maintenance, and operation of these systems may be subject to state and local regulations. State regulations generally involve registration, licensing, and compliance with specific requirements. When regulations for independent oversight do not apply, it is desirable to establish a mechanism for independent oversight to verify system performance and justified use.

6.1 Engineered Controls

Engineered controls include shielding, barriers, system controls, indicators, and safety interlocks. They all are intended to prevent or reduce unintended and unnecessary radiation exposures and thus help ensure that dose limits are not exceeded. Other than controls for emergency termination of radiation emission these features function without requiring actions by the system operators.

Shielding, barriers, and choice of system materials are passive controls. In order to function they must be present in the right places, in the right amounts, and contain the right materials. Shielding attenuates radiation to reduce potential exposures. Materials used in the radiation generating system can be selected to minimize radiation emission from activity induced during the normal use of the system. The choice and specification of shielding materials is dependent on the type and amount of radiation that needs to be attenuated. Filtration of the primary beam can remove unused lower energy emissions which would otherwise contribute to the possible dose without providing any benefit.

Barriers prevent entry into radiation control areas. Barriers can be used when shielding is not practical and there is sufficient distance available to prevent entry into radiation areas. Barriers can either be physical obstructions such as a fence or they can be virtual obstacles such as sensors that trigger system controls that will reduce or terminate radiation emissions as needed. Virtual barrier access controls should be capable of sufficiently fast response time to shut off the beam before an intruding individual can be exposed. The difficulty in implementing effective area control may depend on the population density of the area of use and the speed of intrusion.

System controls are used by operators to initiate, terminate, and set parameters of machine operation and radiation emission. If the controls are unambiguous and can be accessed with the right amount of difficulty they can make administrative controls easier to successfully implement. For example, emergency stop controls should be easy to locate, possibly in multiple locations, and easy to use. The control to initiate radiation emission should be separate from the control that turns on power to the system. It should also require a deliberate action from the operator to initiate radiation emission. A positive means to limit use of the system to authorized individuals such as a key capture switch is prudent. However, it does also require administrative control to implement appropriate control of the key. If a system can operate in multiple modes the current mode should be clearly indicated. An operator action or confirmation is generally desirable when switching modes. Specific beam properties probably should not be adjustable by operators unless sufficient training on the radiation safety implications of those adjustments is provided for the operators.

Interlocks serve to shut off the radiation source if any of the interlocked barriers into beam enclosures or beam paths are breached. Safety interlocks are required for all elements that can affect the dose to the inspection object, including parameters such as voltage and minimum beam speed (for scanning beams). A one-pass beam process will need a method to ensure that the beam does not inadvertently rescan the same part of the interrogated area. Range interlocks are necessary to prevent exposure if an interrogated object is closer than minimum acceptable distances. Electrical interlock settings for inputs to the radiation generating device should be evaluated to determine if they are too high (dose limits could be exceeded) or too low (dose delivered for no benefit). Any maintenance access panels that allow access to an area with radiation in excess of the limit for operators should have an interlock and require a tool to open (can be as simple as a key or a coin).

Operational interlocks should terminate the primary beam in the event of any system problem that could result in abnormal or unintended radiation emission. This should include, but is not limited to: unintended stoppage of beam motion, abnormal or unintended x-ray source output, computer safety system malfunction, termination malfunction, and shutter or beam stop mechanism malfunction. In the event that any of these parameters are out of preset ranges, safety interlocks need to function with sufficient speed that no individual in or on an inspection object can receive more than the dose limit per ADT examination. All such interlocks require independent redundancy such that the failure of any one system component cannot result in the failure of more than one safety interlock. When radiation emission is interrupted due to the function of a safety interlock, clearing the cause of the interlock cannot reinitiate radiation emission. Use of the normal control sequence usually should be necessary for resumption of radiation emission for most interlock conditions.

Other controls, such as in beam dosimetry and other indicators, are intended to alert operators and people that might be inadvertently exposed to the existence of a potential hazard. These may include labels and warnings visible to the operations crew, indicators visible from any point at which radiation emission can be initiated, primary “beam on” indicators visible to operations crew. In addition it is important to provide a means to ensure that system operators have a clear view (or indication) of the primary beam path so that radiation emission can be terminated if necessary.

ADT system design and production documentation shall include safety information. This information may include the following:

- periodic certification and regular testing of safety systems;
- warnings of potential radiation safety hazards (such as unauthorized modification of the system);
- minimum adequate operation procedures and training necessary for operating the system safely;
- minimum preventative maintenance including routine safety/quality control (QC) checks by operating crew;
- technique factors for each operating mode and the beam quality (perhaps stated as the half-value layer of the system in mm of aluminum, of the primary beam);
- dose rate in primary beam under maximum available operating characteristics;
- beam/target profile;
- isodose curves;
- location of the primary beam origin point;
- total dose to inspection object from exposure during one screening;
- detailed isodose map of radiation external to the shielded system;
- expected radiation types in the beam and interrogation location;and expected radiation energy spectra.

6.2 Operational Controls

6.2.1 *Records*

Records need to be maintained of procedures used, QC test results, and correspondence regarding radiation safety questions and incidents, and information on system aging that can affect radiation safety. In the event of a malfunction or accident the relevant records can be essential for determining the root cause and the actions necessary to prevent a reoccurrence of the malfunction or accident. Records are likely to be essential in assessing the dose to inadvertently exposed individuals.

6.2.2 *Training*

All personnel associated with the direct operation of the system should receive training sufficient to operate the system safely prior to performing their assigned duties. All personnel that are expected to perform other duties near an ADT system when it is being operated should receive sufficient training to avoid injury. The scope and depth of the training should be appropriate for the hazards associated with the system.

At a minimum anyone expected to work near an ADT system needs to know the location, appearance or sound, and meaning of all radiation indicators and warnings. They also need to know what actions to take or locations to avoid in response to radiation warnings and indicators. Refresher training should be provided as needed depending on the frequency of use of the ADT system. At a minimum refresher training should be required at least once every twelve months.

6.2.3 *Deployment Plans*

For safe and effective use of an ADT system to be possible, the possible locations of individuals that could be exposed should be determined. Knowledge of these locations can be used to minimize doses by optimization of the deployment location and orientation of the ADT source.

For ADT systems that are rarely used a brief refresher training on radiation emissions and safety features of the ADT system could be essential. The refresher could be a diagram of the probable radiation areas, warnings, and indicators accompanied by an explanation of warning and indicator systems.

The ADT system deployment process should consist of the following elements:

- site analysis to determine the optimal location and orientation to minimize radiation exposures to any individuals in or near the vehicle, object, or building to be examined;
- analysis of the potential for skyshine to contribute significant dose;
- adjustment of the deployment location and orientation accordingly;
- verification that safety systems are functional as installed;
- establishment of an operational area to control access to the extent practical;
- use of physical or virtual barriers to minimize reliance on operators' awareness and ability to view the operational area; and
- verification that radiation generation (or emission) and radiation detection are functional as designed.

Prior to deployment, assessments of the potential dose to operators and scanned individuals should be made based on the expected deployment configuration. These assessments should be updated if the expected deployment configuration differs significantly from the actual deployment configuration.

All configuration and site parameters that can affect radiation safety should be recorded. An appropriate list of parameters to record should be standardized and made available for expected deployment scenarios. Appropriate parameters might include:

- occupancy of surrounding and target locations;
- traffic flow into, through, and from the operational area;
- security issues, including access to the operational area;
- compatibility or interference with other systems at the site (*e.g.*, radiation portal monitors, other screening systems, etc.); and
- use of multiple radiation sources? If yes, what impact does that have on the locations of radiation and high radiation areas?

6.2.4 *System Performance / Quality Controls*

Acceptance tests shall be performed in accordance with procedures developed by the manufacturer prior to deployment of the system. System parameters and performance shall be identified and documented.

During an initial survey, a qualified expert should establish specific QC parameters (*e.g.*, expected doses or dose rate at specific locations under specific conditions) that can be easily verified by the system operators using readily available instrumentation. Such dose and dose rate determinations shall utilize appropriate anthropomorphic phantoms and shall be made in actual usage condition simulations. In addition, test objects shall be utilized in order to verify overall system function. QC parameters should provide the operator with the ability to verify consistent and appropriate operation of the ADT system. Expected measurement error in determining compliance with QC parameters should be documented. The amount of deviation of QC parameters that indicates a system safety problem should be clearly documented. Routine surveillance of QC parameters shall be frequently performed, at a minimum prior to use and on a regular schedule. Action levels shall be selected, which indicate that the ADT system is not working properly and should be taken out of service.

Radiation surveys should be made between and, if necessary, during deployments to verify the appropriate boundary of the operational area, potential doses at operator locations, the presence of activation products, and any other critical parameters as identified in system safety design evaluations. Surveys should be performed:

- during acceptance testing;
- at least once every year and between deployments;
- after any modification, repair, or replacement that affects the radiation shielding, scattered radiation, or radiation production components;
- when making a significant change in operating procedures, such as increases in the time necessary to screen a vehicle, object, or building;

- after any incident which could have damaged the system in such a way that radiation shielding, beam alignment, or other radiation safety features might be compromised; and
- prior to decisions to dispose of the system or components of the system in order to ensure compliance with regulatory requirements associated with disposal of radioactive materials.

6.2.5 *Inadvertent Exposures*

The procedure to document and estimate the dose received by an inadvertently exposed individual should be included in the operating procedures.

Notify the individual of the inadvertent exposure. Include the estimated dose and provide an example that compares the dose to a commonly known source of radiation, for example: "The radiation from this inadvertent exposure is roughly equivalent to ______." For an inadvertent exposure that does not exceed the recommended dose limits for inadvertent and infrequent exposures the only result is a slight increase in potential cancer risk. The radiation dose information associated with an inadvertent exposure should be archived for future reference.

For machine produced radiation, the user should notify the manufacturer of any radiation incidents. For radionuclide based systems, incidents should be reported to the appropriate agency in accordance with applicable regulations.

7. Recommendations

During the course of development of this Commentary, NCRP identified specific areas requiring further consideration and presents the following recommendations:

- Doses potentially received from proposed ADT systems should be modeled with additional computational models (*e.g.*, Monte Carlo code) and compared with the NCRP dose limits.
- A means to differentiate between detection of neutrons from a proton beam and effects of cosmic neutrons on detection systems should be investigated.
- Criteria should be developed for determining when radiation doses greater than the dose limits may be given to noncombatants or to those who do not realize they are combatants (*e.g.*, those who may be unwittingly involved in smuggling SNM).
- A method to track the incident radiation beam during use should be developed. Ideally, the ADT system will be designed so that the beam will not operate if a person is located within the exposure zone. This requires the ability to detect individuals entering the area and the ability to automatically turn off the beam.
- Elaborate and reliable interlock controls (dose, detection quality, movement) should be developed for ADT systems, including:
  - safety interlocks for all elements that can affect the dose to the inspection object;
  - range interlocks to prevent exposure if interrogated object is closer than minimum acceptable distance;
  - electrical interlocks to prevent dose limits being exceeded; and

    - operational interlocks to terminate the primary beam in the event of any system problem that could result in abnormal or unintended radiation emission.

- Radiation detection and measurement systems should be developed to interface with the safety interlocks used with ADT systems to limit or prevent radiation doses above the dose limits.
- Engineered safety systems should be developed to:
    - monitor and control accelerator system parameters;
    - limit the beam size at far distances with passive and/or active collimator systems; and
    - monitor and control the radiation environment in each potential exposure zone.
- Efforts to improve radiation detection and measurement systems (including detectors proper and signal processors) should be made to increase overall ADT system sensitivity and, thus, reduce the required intensity of the interrogation radiation sources.
- Regardless of the type of interrogating radiation that is used, the ideal detector for this application should possess the best overall combination of intrinsic efficiency (sensitivity), obtainable geometries, response time, availability, versatility, and cost. However, ^{3}He should not be considered as a suitable detection material for ADT systems in spite of its desirable qualities, unless a reliable new source is developed.
- Dosimetry should be developed for each type and energy of ionizing radiation associated with the use of ADT systems; proper calibration of dosimetry systems must be developed and used..

- The degree of human health risk should play an important role in the development and use of ADT systems.
- It will be important to determine before systems are deployed what radiation protection regulations will apply and what organization(s) will have regulatory authority over the use of ADT systems.

8. Conclusions

The electron accelerator producing a photon beam is the most mature of the ADT systems in development. To date, DTRA has examined many ADT approaches but has advanced only one system, PITAS, to the demonstration stage. A meaningful comparison of approaches will require carrying several other ADT systems to the demonstration stage.

Procuring equipment that has the appropriate engineered controls is not sufficient to ensure safety. Proper implementation of administrative controls is critical.

The ADT system radiation sources considered in this Commentary could pose a health risk to operating personnel, bystanders, and individuals in the inspected area. These risks involve direct radiation exposure of individuals and secondary exposures associated with the production of activated materials. With a reasonable set of potential exposure assumptions, estimated radiation doses can approach the 5 mSv limit. Designing and operating an ADT system that can meet that limit with any margin of safety will be quite challenging. Analyzing these effects in the context of health risks will assist DTRA in making decisions and developing policies on the types and deployment of candidate ADT systems.

Each of the radiation sources considered for use with ADT systems has advantages and limitations. Likewise, the potential radiation doses to system operators and other persons in the vicinity of the operating ADT system vary considerably with type and energy of the radiation source.

ADT systems will likely be designed and operated to minimize false rejections. One of the consequences is higher radiation dose rates at the SNM location and an associated increase in the number and potential severity of human health protection issues. NCRP could not conclude whether a dose sufficiently low to avoid harm to potential individuals in the inspected area can be achieved with the radiation intensity from the ADT system source necessary for detection of the specified amount of SNM.

Personnel involved in the transport of SNM might be exposed to radiation doses greater than the dose limits. However, an ADT system designed and operated with the safety systems recommended in this Commentary should avoid radiation doses above the dose limits to operators and bystanders. Because it will not be possible to ensure that indivduals are not exposed, the possibility of harm exists.

If the radiation doses were trivial under all plausible scenarios, there would be little reason for public discussion of development and use of ADT systems. But if there were a substantial probability of radiation doses above the dose limits, responses to questions about development and deployment of these systems would be important in a democratic society.

While concerns about exposures are necessary, national security concerns can override issues on health effects and privacy. This facet increases the importance of obtaining enough sufficiently accurate information that can be used to justify the use of ADT systems for screening.

Public concerns regarding the use of ionizing radiation systems for security surveillance and screening of persons and material, including an evaluation of the acceptability to the public and government regulators of potential risks, must be recognized. DTRA should continue to include reviews by outside experts of the health and safety aspects of all new ADT concepts and systems to avoid potential public problems of fear and mistrust.

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